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JOURNAL OF THE AERONAUTICAL SCIENCES

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Technical Trends in Air Transport*

The Sixteenth Wright Brothers Lecture

WILLIAM LITTLEWOOD†

American Airlines, Inc.

SUMMARY

The engineer's conservative approach to a forecast of the future, as a basis for required decisions, is sought by a brief review of some significant technical factors and trends of the past 25 years of American air-transport development, with a summary of where we stand today and a discussion of some extraneous influences. Some trends appear to be firmly established, whereas other directions of development are being greatly modified by numerous factors.

Many apparently obscure technical lessons of the past require re-emphasis by rationalization and illustration to the possible future benefit of the manufacturers, operators, and users of air transportation. The inherent obligations of air-transport operators to the nation, to the traveling public, and to their stockholders require most critical examinations, determinations, and technical decisions in the areas of safety, dependability, comfort and convenience, and economy.

INTRODUCTION

I AM KEENLY AWARE of the privilege and opportunity of presenting the Sixteenth Wright Brothers Lecture. Several months ago, when I accepted the invitation, one of my old and highly respected friends in the industry commented: "I am glad that *you* are going to do the job—now I'll be able to understand a Wright Brothers Lecture!" I have not yet decided whether this was a tribute to hoped-for clarity of expression, a reference to the probably elementary nature of the discussion, or simply an admission of unfamiliarity with higher mathematics and Greek symbols!

This Lecture is somewhat different from those that have preceded it. It is not a summary and report of theoretical studies or of fundamental or applied research in aeronautics, nor is it a review of the investigation and solution of aeronautical design, test, or production engineering problems. It is, rather, a summary of some observations, conclusions, and recommendations in the field of air-transport engineering, based on past experiences and an assessment of the present with an inquiring look at some aspects of the near future. It is possibly appropriate to comment that the opinions expressed herein are solely those of the lecturer and are not necessarily those of his associates or of any organization with which he is connected.

Unfortunately, the classified nature of some pertinent material prevents its inclusion in this paper, but there still appears to be a great deal to say about significant aspects of the past, present, and future of our subject. The subject dealt with is of such scope that space will not permit reference to more than a small percentage of major factors or permit dealing with most of those in comprehensive fashion. Any one of the subjects referred to would encompass material adequate for a series of lectures. It is, rather, the purpose of this paper to investigate the possible existence of indicated trends in the technical aspects of air-transport engineering, to examine the significance and propriety of the directions in which they appear to be leading, and to emphasize some problems urgently requiring solution.

Presented before the Institute of the Aeronautical Sciences in the U.S. Chamber of Commerce Auditorium, Washington, D.C., December 17, 1952.

* The author wishes to acknowledge with grateful appreciation the comprehensive material furnished by Boeing, Curtiss-Wright, Consolidated Vultee, Douglas, Lockheed, and Martin, from their records and files, covering transport airplane developments of their companies. These data, plus that obtained from numerous sources covering many other American transport airplane developments, served to prepare the related tables, charts, curves, and discussions. Detailed grateful acknowledgment has been made in the paper to specific sources of appropriate quotations or other material used. The writer would, indeed, be remiss if he failed to express heartfelt thanks for the help of his air-line engineering associates and particularly to Otto E. Kirchner, who supplied many ideas; planned and supervised preparation of slides, charts, and curves; and further assisted by making additional presentations of the Lecture at other meetings.

† Vice-President—Engineering.

FOKKER F-10 TRIMOTOR

HAMILTON ALL METAL

FORD TRIMOTOR

STEARMAN MAIL PLANE

FAIRCHILD FC2W2

FIG. 1.

AIR TRANSPORTS OF THE PAST

The inherent conservatism of an engineer makes him a disappointing prophet. His vision consists primarily of projections into the future of trends established in the past, suitably modified by recognized influences of all kinds. But, despite the limitations, and in order to evaluate our present position and to judge in what directions we are tending, we will take a quick look at the past.

Established air transportation in America is little more than 25 years old. In that time tremendous technological changes have occurred in air-transport equipment and its performance and use. It is easy to forget many of the lessons of the past. It is not only interesting and refreshing to those who lived and worked through those rapidly changing times, but, to them and to the younger members of the aviation engineering profession who were not part of those experiences, there is real benefit in reviewing some of the important steps and significant lessons of adolescent aviation.

Let us see what has happened to U.S. transport airplanes during the past 25 years. At the beginning of this period, ushered into commercial significance by Lindbergh's historic flight of May, 1927, we had just about outgrown the "stick and wire" models of the early days. The infant industry in America was manned largely by rugged individualists, many of whom were barnstorming pilots and few of whom were sound business men or engineers—since there was little engineering background or apparent stability to this enterprise! There were many financially minded promoters, more interested in Wall Street than the development of the industry, and numerous enthusiasts and visionaries, some of whom truly saw the ultimate military and commercial possibilities of this yawning, young giant, but more of whom were just afraid they would miss out on the excitement of this new adventure. They were all motivated by a desire to fly at any cost—which they did! One slogan of air transportation in those days was: "The more you fly, the more you lose!" The echo is still heard—occasionally!

With such a background (or lack of it), there was naturally, a completely unsettled condition as to transport airplane types, materials, and methods of construction. The Jennies, DH's, Standards, and their contemporaries with their Curtiss OX5, Hispano Suiza, Hall-Scott, and Liberty engines had largely disappeared, but the preponderance of airplanes was still of the small, mail-only type, since the origin of commercial aviation lay in the carriage of mail. A few somewhat larger airplanes of all types carried mail and tolerated a few passengers. And, with the impetus of the more advanced European air transport background, there had begun to be a few even larger transports, designed

to carry passengers with some degree of comfort, as well as to transport mail and a little cargo.

We had the European-American Fokker development of the plywood wing airplane with cloth-covered fuselage, typified by the F-10 trimotor and the single-engined Super Universal, with P. & W. Wasps. Concurrently, we had the all-metal airplanes of truss frame construction covered with corrugated, light-metal skin, such as the Hamilton single engine with P. & W. Hornet and the Ford trimotors with Wright J-5's and P. & W. Wasps. (See Fig. 1.) There was also a vast array of wooden or welded steel, cloth-covered wing and fuselage airplanes, such as the Pitcairn PA series of Mail Planes, the Fairchild FC series of Passenger and Mail Planes, the TravelAir and Stearman Mail Planes, diversely equipped with single Wright J-5 and J-6 and P. & W. Wasp engines.

Table I gives a general summary of Boeing transports to date; Table II gives a list of Lockheed transports; Table III and IIIA are compilations of Douglas transports; Table IV shows Convair transports; and Table V shows Martin and Curtiss-Wright transports.

We must not forget many early and later transports developed by other manufacturers, some of whom have disappeared from the scene or have diverted their attention largely to other activities. Among them were the Loening single-engined amphibian, the Sikorsky S-38 Twin-Wasp amphibians sometimes used in domestic transport, and the associated Sikorsky models like the S-42, four-engined flying boat used for long-range overwater operation. (See Fig. 2.) There was also the Fairchild Pilgrim Model 100 fitted with either single Cyclone or Hornet engine. (See Fig. 3.) This was a single-pilot, high-wing plane of steel and fabric construction fitted with nine passenger seats—including three backward-facing seats! It was, to the best of my knowledge, the first American transport airplane designed as a result of an extensive engineering study and built to airline specifications. In the Stinson family, we found passenger transports of the strut-braced, high-wing, monoplane type in the Models T and U and of the low-wing type in the Model A, each powered with three Lycoming engines. These were all essentially steel, fabric-covered structures. In addition to its more current transport models, Martin earlier developed the Martin Clipper, long-range, overwater flying boat, and later, of course, the large Mars flying boat used by M.A.T.S.

Throughout the early period, there was evident a wide, enthusiastic, and often highly unscientific search for the most suitable types, designs, materials, and methods of construction for economically sound and safe transport aircraft. The early airplanes were replete with all sorts of unique designs and details of construction and were fitted with equipments of all degrees of excellence and suitability. Gradually there emerged from this confusion, largely by trial and error assisted by budding engineering efforts and hard-earned knowledge, many variations of all-metal, internally braced, stressed-skin structures, typified first, as shown in the tables, by the single-engined Boeing Monomail in 1930, and later by the twin-engined Boeing 247D in 1934;

TABLE I

BOEING TRANSPORTS

MODEL	CERTIFICATION DATE	PURPOSE	GROSS WEIGHT	TYPE	POWER PLANT	SPEED HIGH	SPEED CRUISING	ULTIMATE RANGE-MI.	CONSTRUCTION & MATERIALS	REMARKS
ACTIVE B-1	1919	P-2-4 MAIL	3,850	BIPLANE BOAT	1 HALL SCOTT OR 1 LIBERTY	90	80	400	WOOD WIRE FABRIC	WOOD PROPELLER (1 BUILT) BOAT-MAIL
40A	1927	P-2 C-1200#	4,652	BIPLANE LAND	1 P&W WASP	135	125	550	TUBE & FABRIC FUSELAGE-WOOD & FABRIC WINGS	2 BL. ADJ. METAL PROP-FIXED LANDING GEAR
80A	1928-30	P-18 CARGO-2778 LBS.	17,500	BIPLANE LAND	3 P&W HORNET A	139	125	460	WD. STEEL FRAME DURAL RIBS-FABRIC COVERED	3 BL. ADJ. METAL PROP-FIXED LANDING GEAR
221 MONOMAIL	1930	P-6 CARGO-750 LBS.	8,000	LOW WING MONO LAND	1 P&W HORNET B	158	135	600	ALL METAL(17S) INTERNALLY BRACED-TUBE & METAL SKIN	3 BLADE ADJ. METAL PROP RETRACTABLE GEAR
247D	1934-35	P-10 C-2400 LBS.	13,650	LOW WING MONO LAND	2 P&W WASP	200	189	745	ALL METAL(24S) STREAMLINED INTERNALLY BRACED	3 BLADE ADJ. METAL PROPS RETRACTABLE GEAR-DE ICED
SA-307B STRATOLINER	1940	P-33 C-7681 LBS.	45,000	LOW WING MONO LAND	4 W-1820 G-105	246	220	2390	ALUMINUM ALLOY AND STEEL	(10 BUILT) H.S. 3 BL. HYDROMATIC FFCS PROPS-PRESSURIZED
A-314 (CLIPPER)	1941	P-85 CARGO-10826 LB.	84,000	HIGH WING BOAT	4 W G-2600	199	164	5200	"	H.S. HYDROMATIC FFCS PROPS
377 STRATOCRUISER	1948	P-89 CARGO-17,100 LBS.	145,800	LOW WING MONO LAND	4 P&W 4360 T. SUPRCHG.	351	300	4600	"	H.S. OR C.W. PROPELLERS FFCSR
INACTIVE 417	1947	P-20 C-15601B	18,750	HIGH WING MONO LAND	2-W-C7BA	224	182	——	"	NOT BUILT-H.S. FFCS PROPS
431	1945	P-30 CARGO-2817 LBS.	36,000	HIGH WING MONO LAND	2 P&W R-2800	280	180	1000	"	NOT BUILT (DC-3 REPLACEMENT) H.S. FFCS PROPELLERS

P = PASSENGER C = CARGO W = WRIGHT P&W = PRATT & WHITNEY H. S. = HAMILTON STANDARD MONO = MONOPLANE FFCS = FULL FEATHERING CONSTANT SPEED FFCSR = FULL FEATHERING CONSTANT SPEED REVERSE ADJ. = ADJUSTABLE C.W. = CURTISS WRIGHT WD. = WELDED BL. = BLADE T = TURBO

TABLE II

LOCKHEED TRANSPORTS

MODEL	CERTIFICATION DATE	PURPOSE	GROSS WEIGHT	TYPE	POWER PLANT	SPEED HIGH	SPEED CRUISING	ULTIMATE RANGE-MI.	CONSTRUCTION & MATERIALS	REMARKS
ACTIVE VEGA	1926 & 1929	P=4-6 M=21 C.F.	3470 TO 4500	HIGH WING MONO	1-W-J5 OR 1 P&W WASP	196	180	660	MOLDED PLYWOOD	FIXED GEAR PROPS-ADJUSTABLE
ORION	1930	P=6 M=18 C.F.	5800	LOW WING MONO	1 P&W WASP	227	205	720	"	RG PROPS-CONTROLLABLE
ELECTRA L-10	1933	P=10 C=800#	10,500	LOW WING MONO	2 P&W WASP JR.	202	190	880	AL. ALLOY INTERNALLY BRACED	RG PROPS-C S
L-12A	1935	P=6 C=865#	9200	LOW WING MONO	2 P&W WASP JR.	223	212	1060	"	RG PROPS-C S
L-14H	1937	P=11 C=2700#	17,500	MID WING MONO	2 P&W HORNET	244	223	2060	"	RG PROPS-C S
LODESTAR L-18	1939	P=14 C=3400#	17,500	MID WING MONO	2 P&W HORNET	263	241	1875	"	RG PROPS-C S
CONSTELLATION L-049	1946	P=51 C=14,250	90,000	LOW WING MONO	4 WRIGHT 3350	344	314	5000	"	PR-RG PROPS-FFCS
L-749	1947	P=44 C=13,500	102,000	LOW WING MONO	4 WRIGHT 3350	356	328	5430	"	PR-RG PROPS-FFCSR
L-1049	1951	P=75 C=13,120	120,000	LOW WING MONO	4 WRIGHT 3350	347	318	5300	"	PR-RG PROPS-FFCSR
L-1049E	1953	P=63 C=13,860	133,000	LOW WING MONO	4 WRIGHT COMPOUND	376	335	4930	"	PR-RG PROPS-FFCSR
INACTIVE EXCALIBER (L-44)	-	P=21 C=350 C.F.	27,500	LOW WING MONO	4 P&W WASP	241	180	2180	"	RG PROPS-C S
SATURN L-75	-	P=14 C=1450#	16,000	HIGH WING MONO	2 W-1820 CYCLONE	252	206	2040	"	RG PROPS-FFCS
CONSTITUTION L-89	-	P=168 C=34,109	184,000	MID WING MONO	4 P&W 4360	307	287	5100	"	RG PROPS-FFCS

M=MAIL P=PASSENGERS RG=RETRACTABLE GEAR FFCSR=FULL FEATHERING CONSTANT SPEED REVERSE
C=CARGO (LBS) C.F.=CUBIC FEET PR=PRESSURIZED FFCS=FULL FEATHERING CONSTANT SPEED W=WRIGHT

TABLE III

DOUGLAS TRANSPORTS

ACTIVE

MODEL	CERTIFICATION DATE	PURPOSE	GROSS WEIGHT	TYPE	POWER PLANT	SPEED HIGH	SPEED CRUISING	ULTIMATE RANGE-MI.	CONSTRUCTION & MATERIALS	REMARKS
M-1-2-3	*1926	MAIL	4,968	BIPLANE	1 LIBERTY	145	110	650	TUBING-TIE ROD FUSELAGE - SPRUCE & WOOD WINGS-FABRIC COVERED	FIXED LANDING GEAR - WOOD PROPELLER
C-1	*1925	U.S. TROOP TRANSP'T.	——	BIPLANE	1 LIBERTY 12	121	——	——	"	"
DC-1	1933	P=12-18 C-WL=1000 LBS.	17,500	LOW WING MONOPLANE LAND	2-W-1820 F3	210	190	1000	GENERALLY 24S INTERNALLY BRACED	RETRACTABLE L.G. H.S.-3 BLADE-HYDROMATIC
DC-2	1934	P=14 CARGO=1740 LBS.	18,560	"	"	"	200	1060	"	"
DC-3	1936	P=21-24 C-WL=1950 (14 DST)	25,200	"	2 P&W 1830 OR W1820 G	211	191	1480	"	"
DC-4 (C-54)	(1943)-46	P=44-50 C-WL=5138 LBS.	73,000	"	4 P&W R-2000	234	219	4240	"	"
DC-6	1947	P=52-68D C-WL=7320 LBS	93,100	"	4 P&W R-2800	350	304	4500	GENERALLY 24S INTERNALLY BRACED +75S	RETRACTABLE L.G. PRESSURIZED 4 C.W. OR H.S. FFCSR PROPS
DC-6A	1951	C-WL=30,150 LBS.	107,000	"	"	359	315	5000	"	RETRACTABLE L.G. PRESSURIZED 4 H.S. FFCSR PROPS
DC-6B	1951	P=66D C-WL=11,930 LBS	100,000	"	4 P&W R2800 CB16	364	315	5000	"	"
DC-7	1953	P=69D C=13,980 LBS.	122,000	"	4-W 3350 COMP.	393	360	4445	" + T	"

P = PASSENGER P&W = PRATT & WHITNEY FFCSR = FULL FEATHERING CONSTANT SPEED REVERSE DST = SLEEPER
C = CARGO H.S. = HAMILTON STANDARD COMP = COMPOUND ENGINES T = TITANIUM D = DAYPLANE
W = WRIGHT C.W. = CURTISS WRIGHT CS = CONSTANT SPEED L.G. = LANDING GEAR
* = FIRST FLIGHT DATE WL = WEIGHT LIMITED

TABLE III-A

DOUGLAS TRANSPORTS

MODEL	CERTIFICATION DATE	PURPOSE	GROSS WEIGHT	TYPE	POWER PLANT	SPEED HIGH	SPEED CRUISING	ULTIMATE RANGE-MI.	CONSTRUCTION & MATERIALS	REMARKS
INACTIVE										
DC-4E	1939	P+C FUSELAGE SPACE INCOMPLETED	65,000	LOW WING MONOPLANE LAND	4 P&W R-2180	242	200	1750	GENERALLY 24S INTERNALLY BRACED	1 ONLY EXPERIMENTAL (ABANDONED)
DC-5A	*1940	P=22 C-SL=3000 LBS	23,500	"	2-W-18209H	265	241	1165	"	11 ONLY EXPERIMENTAL (ABANDONED)
DC-7 (OLD)	*1946	P=108 C-SL=11690 LBS.	162,000	"	4 P&W 4360	306	262	5000	"	(ABANDONED)
DC-8 (OLD)	*1947	P=38-48 C-WL=1000 TO 6000 LBS.	39,500	LOW WING MONOPLANE LAND (PUSHER)	2-V-1710 ALLISON	290	270	—	"	EXPERIMENTAL (ABANDONED) 3 BLADE CONTRA ROTATING PROPELLERS
DC-9	*1948	P=28 C-SL=3500 LBS	31,445	LOW WING MONOPLANE LAND	2-W-1820 (2 SPEED)	—	258	2590	"	EXPERIMENTAL (ABANDONED) 2 C.W. ELECTRIC PROPELLERS
SUPER DC-3	1950	P=31 C=3030 LBS.	31,000	"	2-W-1820C-9H	270	250	2200	"	2 H.S. FULL FEATHERING PROPS

P = PASSENGER P&W = PRATT & WHITNEY * = PROPOSAL DATE
C = CARGO H.S. = HAMILTON STANDARD SL = SPACE LIMITED
W = WRIGHT C.W. = CURTISS WRIGHT WL = WEIGHT LIMITED

TABLE IV

CONSOLIDATED VULTEE TRANSPORTS

MODEL	CERTIFICATION DATE	PURPOSE	GROSS WEIGHT	TYPE	POWER PLANT	SPEED HIGH	SPEED CRUISING	ULTIMATE RANGE-MI.	CONSTRUCTION & MATERIALS	REMARKS
ACTIVE										
COMMODORE	1929	P=20 75 CU.FT.	17,600	HIGH WING MONO BOAT	2 P&W HORNET	128	108	1000	ALUMINUM ALLOY & FABRIC WING ALUMINUM HULL	BOAT
FLEETSTER	1931	P=6 60 CU.FT.	5,900	HIGH WING MONO LAND	1 P&W HORNET B	180	153	750	PLYWOOD FUSELAGE-ALUMINUM WING & TAIL	FIXED PITCH PROPELLER FIXED GEAR
VULTEE V1A	1934	P=8 C=1600 LBS.	8,500	LOW WING MONO LAND	WRIGHT 1820 RF2	235	215	—	ALUMINUM MONOCOQUE	RETRACTABLE GEAR 1 ADJUSTABLE PROPELLER
PBY-5A	1945	P=22	28,000	HIGH WING MONO AMPHIBIAN	2 P&W 1830	195	139	750	ALUMINUM ALLOY-FABRIC COVERED CONTROLS	MILITARY CONVERSION
240	1947	P=40 CARGO=3000 LBS.	41,790	LOW WING MONO LAND	2 P&W R-2800	326	291	1620	ALUMINUM ALLOY	RETRACTABLE-TRICYCLE GEAR H.S. OR C.W. FFCSR
340	1952	P=44 CARGO=3600 LBS.	47,000	LOW WING MONO LAND	2 P&W R-2800-CB-16	317	284	1830	ALUMINUM ALLOY	RETRACTABLE-TRICYCLE GEAR H.S. OR C.W. FFCSR
INACTIVE										
39	1942	P=48 CARGO=12,600 LBS.	66,500	HIGH WING MONO LAND	4 P&W R-2000	300	240	3300	ALUMINUM ALLOY	EXPER. ONLY-RETRACTABLE-TRICYCLE GEAR
110	1944-45	P=30 C=2080 LBS.	36,000	LOW WING MONO LAND	2 P&W R-2800	314	270	1250	ALUMINUM ALLOY	EXPER. ONLY-RETRACTABLE-TRICYCLE GEAR
C-99	1943	P=204 OR 100,000#	328,000	MID WING MONO LAND	6 P&W R-4360	299	235	4750	ALUMINUM ALLOY	EXPERIMENTAL ONLY 2 DECKS

P = PASSENGER P&W = PRATT & WHITNEY FFCS = FULL FEATHERING CONSTANT SPEED
C = CARGO H.S. = HAMILTON STANDARD FFCSR = FULL FEATHERING CONSTANT SPEED REVERSE
MONO = MONOPLANE EXPER. = EXPERIMENTAL

TABLE V

CURTISS-WRIGHT TRANSPORTS

MODEL	CERTIFICATION DATE	PURPOSE	GROSS WEIGHT	TYPE	POWER PLANT	SPEED HIGH	SPEED CRUISING	ULTIMATE RANGE-MI.	CONSTRUCTION & MATERIALS	REMARKS
ACTIVE C-46	1940	P=40 OR C=2300 CU. FT.	50,000	LOW MID WING MONO	2 PRATT & WHITNEY R-2800	265	242	1000	ALUMINUM ALLOY	RETRACT GEAR
INACTIVE KINGBIRD	1930	P=8	6115	HIGH WING MONO	2 WRIGHT J-6-300	135	115	840	STEEL TUBE FABRIC	FIXED GEAR
CONDOR	1929	P=18	17,900	BIPLANE LAND	2 CURTISS CONQUERER	145	125	800	ALUM. & STEEL TUBE-FABRIC	FIXED GEAR
T-32	1933	P=18D OR P=12S	17,900	BIPLANE LAND	2 WRIGHT 1820F	170	147	500	STEEL TUBE FABRIC	RETRACT GEAR (1ST PRODUCTION SLEEPER PLANE)

GLENN L. MARTIN TRANSPORTS

MODEL	CERTIFICATION DATE	PURPOSE	GROSS WEIGHT	TYPE	POWER PLANT	SPEED HIGH	SPEED CRUISING	ULTIMATE RANGE-MI.	CONSTRUCTION & MATERIALS	REMARKS
202	1947	P= 36 C=3260	39,900	LOW WING MONO LAND	2 PRATT & WHITNEY R-2800-CB-16	311	286	2020	ALUMINUM ALLOY	RETRACTABLE-TRICYCLE GEAR H.S. FFCSR
404	1951	P= 40 C= 1000	44,900	"	"	312	284	2525	"	"

P= PASSENGERS D=DAY SEATS MONO=MONOPLANE FFCSR=FULL FEATHERING CONSTANT SPEED REVERSE
C=CARGO S=SLEEPER BERTHS C.W.=CURTISS WRIGHT H.S.=HAMILTON STANDARD

LOENING AMPHIBIAN

SIKORSKY S-38

SIKORSKY S-42

FIG. 2.

by the twin-engined Douglas series starting with the DC-1 and DC-2 in 1933; by the Lockheed twin-engined series starting with the Lockheed Electra Model 10 in 1933; and by the single-engined Vultee V-1A about the same time. (See Fig. 4.)

During the latter half of this period many additional airplanes intended for transport use were proposed and carried to varying degrees of completion or use. A few interesting ones included: the Lockheed 44 (Excalibur); the Lockheed Constitution; the Lockheed L-75 (Saturn); the original Douglas DC-4E; the Douglas DC-5; the original Douglas DC-8; the original Douglas DC-7; the Douglas DC-9; the Boeing 417 and 431; the Curtiss-Wright CW20 (finally developed as the C46); the Martin 303; the Republic Rainbow; the Consolidated Models 39, 110, and C-99; etc. (See Fig. 5.)

Following the earlier all-metal airplanes, increases in capacity and performance, made possible by the availability of larger power plants, brought into being in 1936 the Douglas DC-3 with two Wright Cyclone 1820 or P. & W. 1830 engines. (See Fig. 6.) This was, I believe, the first American transport to show a favorable net difference between costs and revenues at reasonable load factors and for a substantial spread of operating ranges. This benefit has largely disappeared today with the rising tides of costs. In an effort to re-establish the early advantages of the DC-3, Douglas, in 1950, brought out the frequently planned Super DC-3, improved as to power, capacity, and flexibility but not sufficiently so to overcome the appeal of then available low-cost war surplus DC-3's nor the advantages of the more modern designs in its contemporary competitors.

The trend in transport design crystallized in all-metal structures with increasing external aerodynamic cleanness made possible as aerodynamic lessons were learned and the principles of internally braced, stress-skin structures were established. Uniform sections in wing spars and structure have given way to tapered elements consistent with the weightsavings possible with the cantilever beam requirements, and there has been an increasing transfer of stress, strength, and stiffness to skin structure as performances and loads have increased. We still have innumerable detail design differences between different engineering groups, but the basic principles of design and construction have become amazingly uniform based on the determination and expression of sound engineering principles and knowledge of how to achieve maximum strength for minimum weight to meet the established load conditions.

Power-Plant Development

Let us now examine the story of power plants. Early transports were often single-engined or trimotored. We did have one strange phenomenon flash across the horizon about 1930 in the form of the twelve-engined German-Swiss Dornier DOX. (See Fig. 7.) Without

FAIRCHILD PILGRIM-100

STINSON MODEL "U" TRIMOTOR

STINSON MODEL "A" TRIMOTOR

FIG. 3.

a clear definition of engine-out requirements in that era of relatively undefined regulations or specifications for transport aircraft and in the then prevailing spirit of adventure, there was general industry, if not public, acceptance of single-engined aircraft. They were admittedly quite efficient as to flight costs. There was also broad acceptance of the three-engined principle, where engine-out performance gave, generally, a good service ceiling. In spite of its lacks involving fire risk, noise, dirt, and vibration, there was evidenced no too serious industry objection to an engine in the nose of the fuselage.

A rather comprehensive engineering study issued in 1931 seemed to prove beyond the shadow of a doubt that an economically sound transport could not be built with two of the then available engines. One engine appeared acceptable, three and four were eminently satisfactory, but two were shown to be quite unsound. This conclusion was quickly proved erroneous by subsequent developments we have mentioned. There began, at about that time, an amazing development of engine rated powers, both by specific increases and by rating differentiation between take-off and METO powers, which were among the principal factors in nullifying the authenticity of the report and its conclusions.

You may remember the innumerable engine developments that characterized the early period of transport

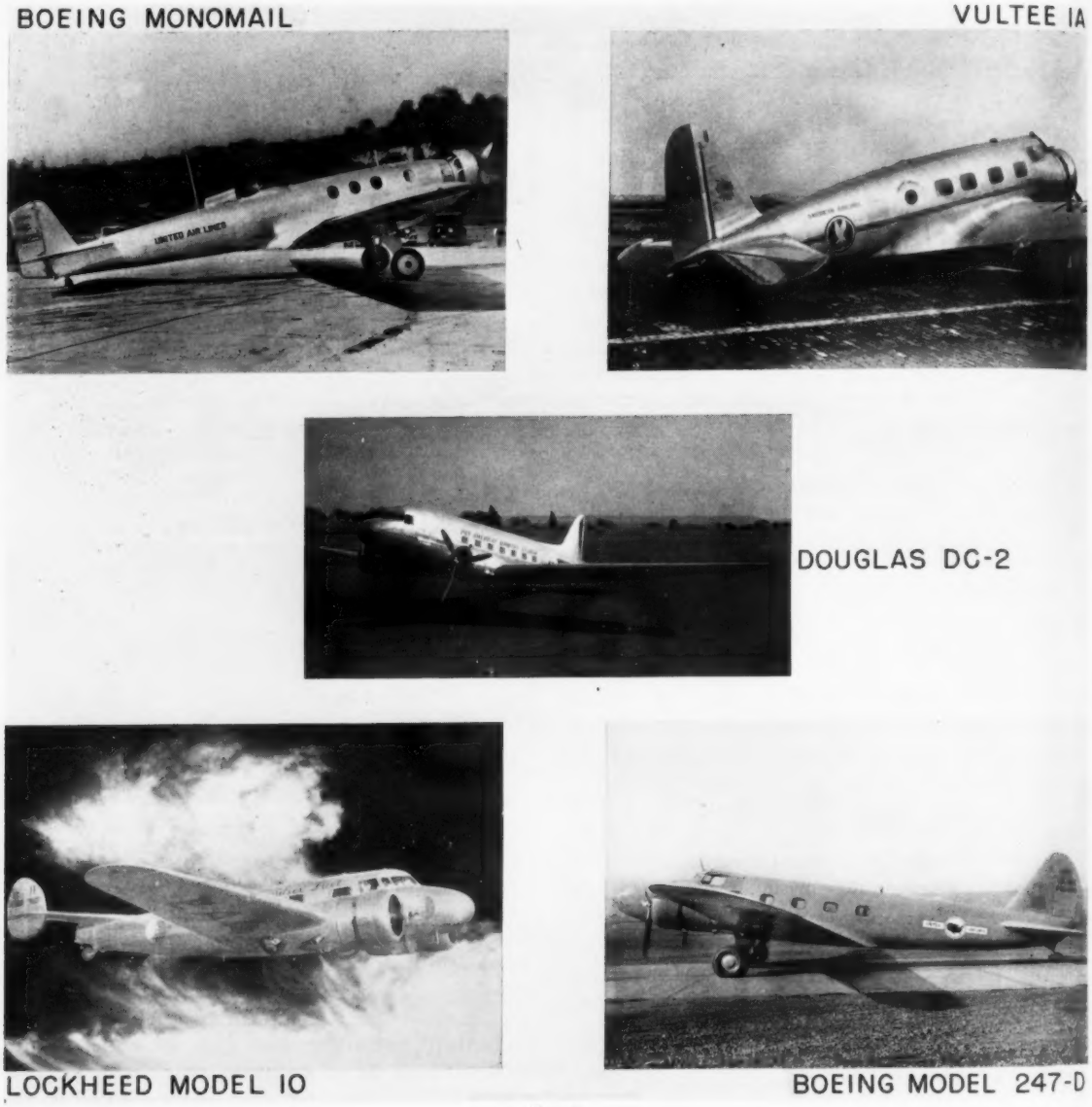


FIG. 4.

history. There was some discussion of gas turbines, but there was general agreement that the cycle efficiency was low and that the temperature problems were so great that such an application was impractical. Its eventual availability as turbojet or turboprop awaited the development of high-temperature materials and improvements of compressor and combustion efficiencies provided by other applications and needs—partly by exhaust supercharger developments—and finally sparked by British drive under the urge of national pride, economic need, and international competition.

There were early strenuous efforts to develop the diesel-type engine for aircraft. In the early 1930's several designs of cam-type reciprocating engines were carried well along toward moderately successful operation, but for one or another technical or economic reason these were abandoned. A number of small engines with no direct transport application, some with unique features, was also produced.

The engine development pattern, however, became definite as time proceeded. With the Wright series, there was the early widely used radial air-cooled J-4 and J-5 following their more or less experimental predecessors and the liquid-cooled Conqueror; then, the J-6 series with five, seven, or nine cylinders; then, the Cyclone R-1820 nine-cylinder series, leading eventually to the double Cyclone R-3350, which in its ultimate compounded form represents the most advanced reciprocating-engine engineering available today, particu-

LOCKHEED CONSTITUTION

DOUGLAS DC-4E

DOUGLAS DC-5

CURTISS C-46

REPUBLIC RAINBOW

FIG. 5.

DOUGLAS DC-3

FIG. 6.

GERMAN-SWISS DORNIER DOX

FIG. 7.

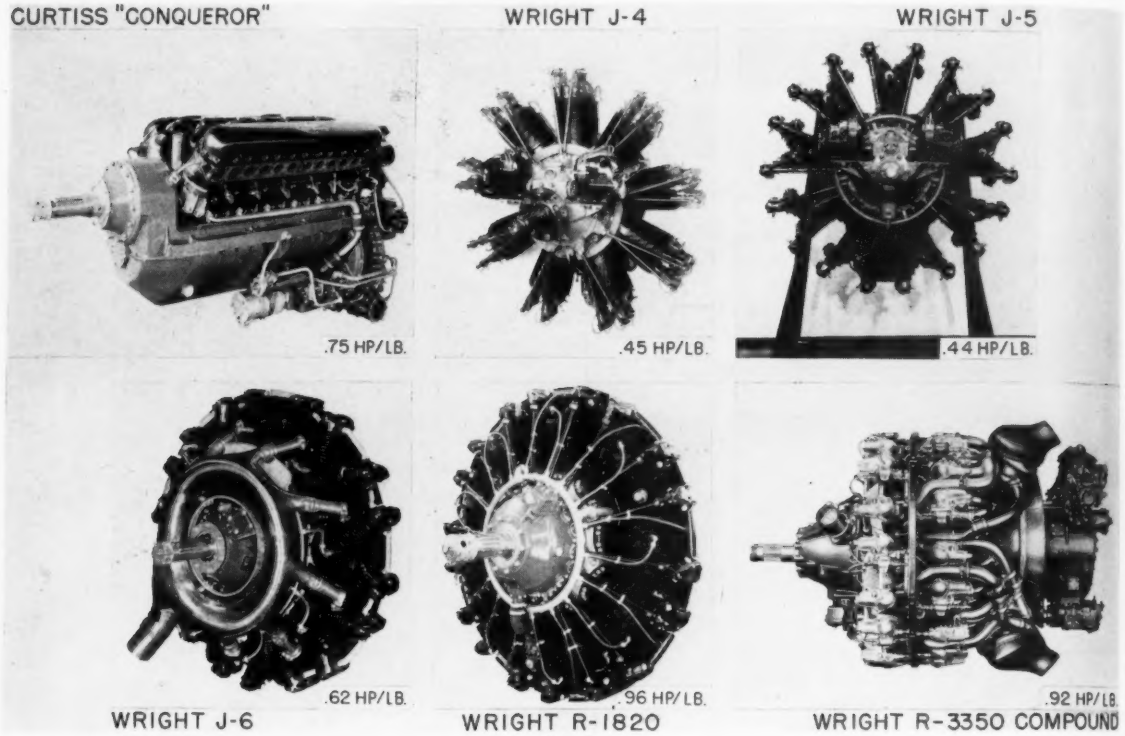


FIG. 8.

larly with respect to fuel economy. (See Fig. 8.) In the P. & W. series, there were the nine-cylinder Wasps and Hornets; then the Wasp Jr. and the 14-cylinder R-1830, patterned somewhat after the Armstrong Siddeley Jaguar; with, later, the R-2180, the R-2000, and the R-2800, which has become the most widely used modern transport engine of today; and, finally, the largest radial model, the 28 cylinder R-4360. (See Fig. 9.)

The early liquid-cooled engines, including the war-developed Liberty and its predecessors and the Curtiss Conquerer, passed out with the competing development of the lighter and simpler radial air-cooled types. It was particularly interesting, in view of this trend, to note that during World War I the liquid-cooled Allison V-1710 achieved noteworthy success paralleling the somewhat similar Rolls-Royce Merlin. It made an outstanding contribution to military operation, although it never found any active place in commercial transportation.

The amazing developments of rated power outputs of all of these aircraft engines, without change of basic displacement sizes, came about as a result of continuous refinement and exhaustive testing on the stand and in the vast laboratory of military and commercial use, which determined and helped eliminate one after another detail weakness. The Wright 1820 and P. & W. 1830 engines grew, in some 20 years, from approximately 500 to 1,500 hp. by this process of refinement, and all the other models showed parallel development.

There was some 25 per cent improvement during the same period in specific fuel consumptions, but the outstanding developments were in total power with reduced weight and greatly improved flexibility and reliability of operation.

We have today reached a point in the trend of required powers or thrusts such that, with the indicated advent of the turboprop and turbojet, see Fig. 10, there does not appear to be any likelihood of new powerplant developments of the larger reciprocating type. There is still great opportunity for engineering refinement to make the power plants of reciprocating type currently in use, and to be used for a number of years to come, completely adequate with respect to reliability and economy.

Early air-cooled engines were installed with their cylinders fully exposed to the atmosphere. (See Fig. 11.) It was not unnatural, in the absence of any information to the contrary, to assume that such an arrangement promoted the most favorable cylinder cooling. Early research in England, however, developed the principle of the Townend ring—a relatively narrow cylindrical band of cambered section surrounding the outside diameter of the engine cylinders. The principal purpose was to reduce drag by the elimination of the major turbulence that was inevitably associated with the irregular cylinder contours. Additional research in America resulted in the development of the N.A.C.A. cowl, which gave further reductions in drag and substantial improvements in effective engine cooling. With

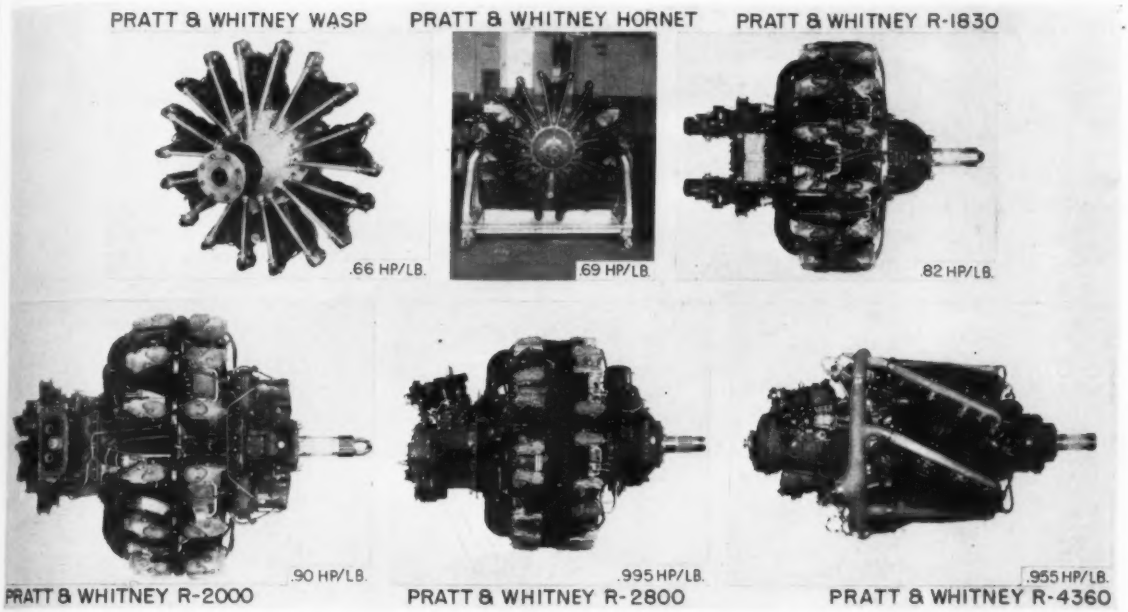

PRATT & WHITNEY WASP
.66 HP/LB.
PRATT & WHITNEY HORNET
.69 HP/LB.
PRATT & WHITNEY R-1830
.82 HP/LB.
.90 HP/LB.
PRATT & WHITNEY R-2000
.995 HP/LB.
PRATT & WHITNEY R-2800
.955 HP/LB.
PRATT & WHITNEY R-4360

FIG. 9.

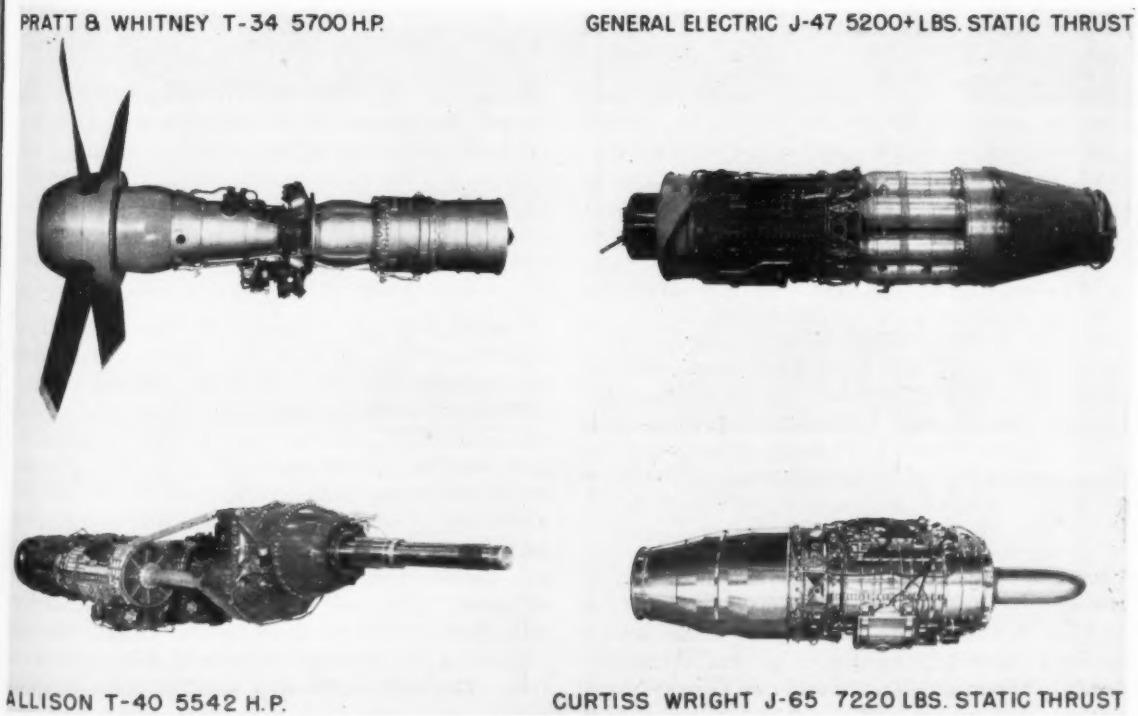

PRATT & WHITNEY T-34 5700 H.P.
GENERAL ELECTRIC J-47 5200+ LBS. STATIC THRUST
ALLISON T-40 5542 H.P.
CURTISS WRIGHT J-65 7220 LBS. STATIC THRUST

FIG. 10.

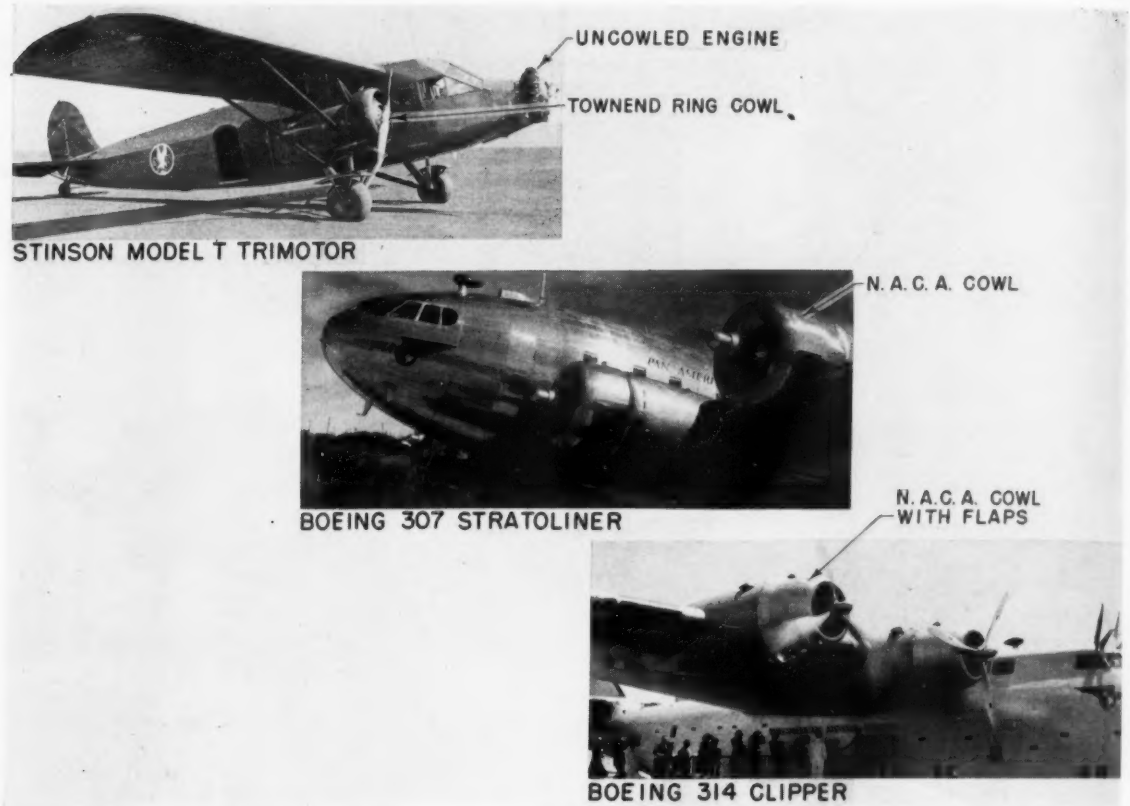


FIG. 11.

the development over the years of deeper and more narrowly spaced fins and efficient baffles, the airflows and horsepower required to meet cooling needs were reduced, and tremendous increases in cooling capacity were achieved, permitting substantial improvements in specific cylinder output. The ultimate development of adjustable trailing-edge cowl flaps permitted the varying of cooling capacity and drag to fit more closely the high heat requirements of maximum power at take-off and climb and the minimum drag requirements of cruising and descent with lowered heat loads. This has added substantially to airplane performance efficiencies. You will later note that the character of this development is similar to that which applied to progressive improvements in propeller types and efficiencies.

PROPELLER TRENDS

Propellers have given us a truly amazing story, for without the developments that have occurred we could never have realized the benefits of the aerodynamic cleanness and improved structural weights and strengths of our airplane, nor could we have developed the potential powers and thrusts from our engines. The earliest commercial propellers were of the fixed-pitch, wooden type, shortly paralleled in use by fixed-pitch metal propellers of the Reed twisted-blade type. (See Fig. 12.) A major step in propeller economy was the early development of the adjustable-blade propeller, which, by ground adjustment of pitch, permitted the adoption of a setting reasonably suited to the particular requirements of the airplane-engine combination with which it was used. The same period included some development and use of fixed-pitch and adjustable-pitch propellers with Micarta and solid steel blades.

None of these units, however, developed the real potentialities of the power plants. Steps in that direction included the two-position H-S propeller which could be adjusted from the cockpit to a low-pitch position reasonably consistent with the slow air-speed requirements of take-off and initial climb, during which régime the engine could now be speeded up to develop more fully its rated power and thereafter could be set in flight to a high-pitch position as required for reasonable efficiency in cruising at reduced r.p.m. and higher air speed. There was also a CW electric controllable-pitch propeller operable from the cockpit to accomplish a slight additional refinement with variable pitch selection. The next major step was the constant-speed controllable-pitch propeller, which by governor control adjusted from the cockpit would maintain a desirable take-off r.p.m. for maximum power, permitting a continuous advance of propeller pitch throughout that in-

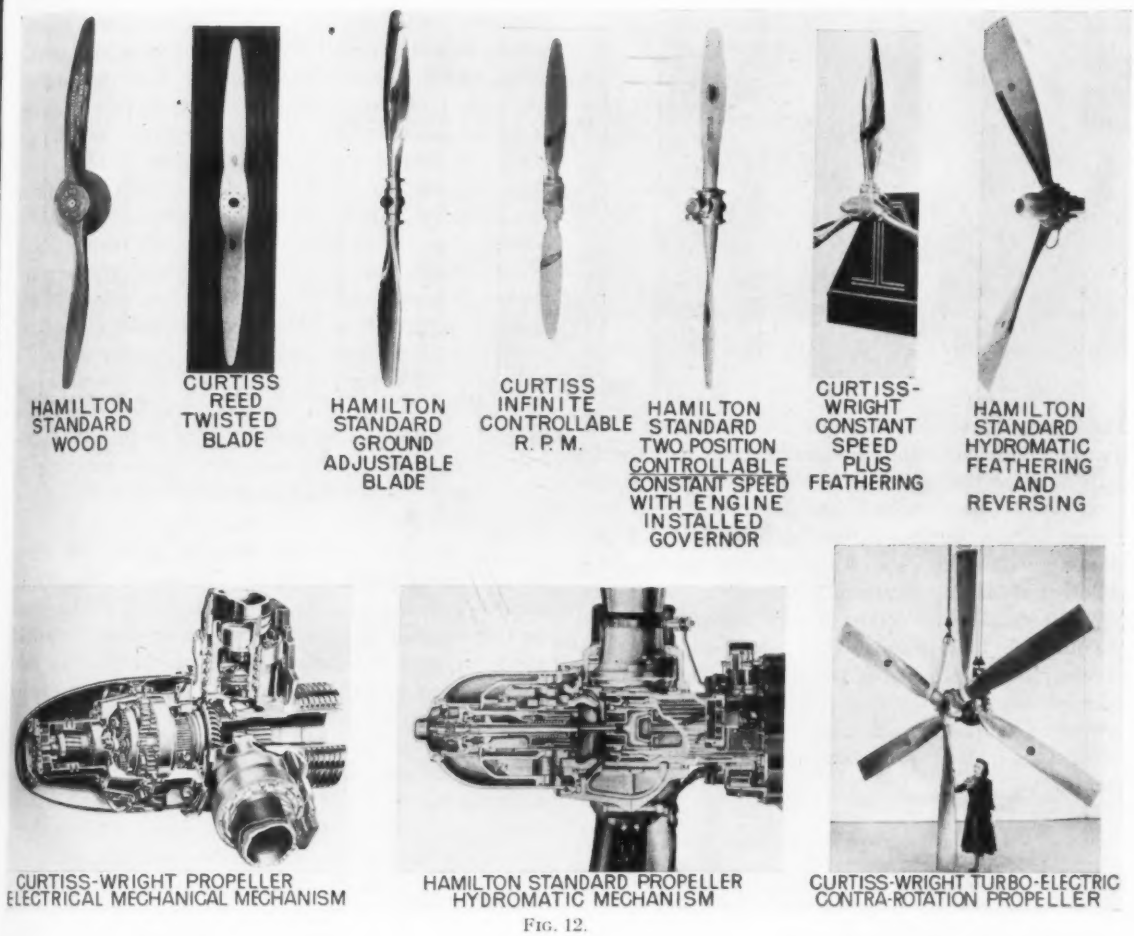

HAMILTON STANDARD WOOD
CURTISS REED TWISTED BLADE
HAMILTON STANDARD GROUND ADJUSTABLE BLADE
CURTISS INFINITE CONTROLLABLE R. P. M.
HAMILTON STANDARD TWO POSITION CONTROLLABLE CONSTANT SPEED WITH ENGINE INSTALLED GOVERNOR
CURTISS-WRIGHT CONSTANT SPEED PLUS FEATHERING
HAMILTON STANDARD HYDROMATIC FEATHERING AND REVERSING
CURTISS-WRIGHT PROPELLER ELECTRICAL MECHANICAL MECHANISM
HAMILTON STANDARD PROPELLER HYDROMATIC MECHANISM
CURTISS-WRIGHT TURBO-ELECTRIC CONTRA-ROTATION PROPELLER

FIG. 12.

creasing speed régime. It could again be set from the cockpit to whatever r.p.m. was desired for cruising or descent to give a proper relationship between engine power and airplane speed performance. Propellers of this type were developed with mechanical, hydraulic, and electrical operating principles. Of these several types, the electrical and hydraulic types have prevailed.

A logical extension of these principles was, first, the development of the feathering propeller extending the ability of the blades to progress to a zero torque position—approximately 90° pitch—which in the event of power-plant failure would prevent additional rotation and progressive mechanical damage to the engine and would reduce to a minimum the drag of the otherwise windmilling propeller, thus greatly enhancing the engine-out performance and controllability of the airplane. The most recent and logical extension of propeller-pitch control has been the development, with both the electrical and hydraulic types, of the reversing principle. This, on election, permits the blades to proceed through zero pitch into a low reverse-pitch condition, where application of power produces reverse thrust on the ground. Innumerable safeguards are provided to prevent accidental reversing in flight. The added safety afforded by the use of this feature is evident from a contemplation of the ability provided to stop the airplane on slippery or icy runways or to arrest the forward motion in the event of emergency landing on a short runway.

In the mid 1930's there were developed and applied the principles of propeller-blade vibration stress analysis, explaining many past failures and preventing many others. The discovery of test techniques to disclose the numerous modes and intensities of vibration stresses and correlate them with engine and installation stress conditions was one of the major steps leading to innumerable modern applications and refinements in this field.

It has been interesting to watch the development of propeller blade designs from the trend toward thin so-called "toothpick" blades with much design emphasis on tip losses to the modern designs involving broad, square tips and substantial blade areas to give high activity factors and absorb the continuously increasing horsepowers available without using excessive numbers of blades or pitches or too large diameters and tip speeds.

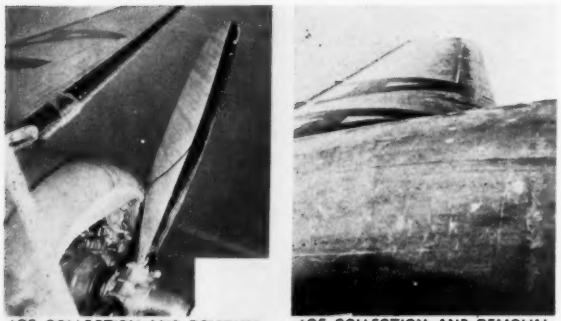


FIG. 13.

The future of propeller development, particularly in the transonic and supersonic tip-speed ranges, may apparently involve the use of extremely thin sections and possibly solid steel blades. The past and present have carried along a continuous development of solid, forged aluminum-alloy blades and a parallel development of hollow steel blades. Numerous schemes have been employed for the construction of such hollow propellers, the only ones built in substantial quantities being those of complex welded plate structures. The extrusion principle may in the future establish a new and improved technique for such units. Weight and strength advantages in large propeller sizes urge such developments.

ICE PROTECTION DEVELOPMENTS

Our air-transport picture of the past 25 years has included essential and parallel developments in every phase of associated engineering and equipment. One of the most important has been the development of ice protection for the airplane, its power plants, and its propellers, as well as for all external equipment such as antenna, radomes, etc. The problem of giving aircraft adequate protection against ice formations, particularly of the atmospheric type affecting the airplane itself, has always appeared to be an extremely difficult one. When we consider, however, that the airplane operates almost entirely in association with one medium only—namely, the atmosphere—except for extremely short periods during take-off and landing, the problem appears to become much simpler than that facing either a land or water vehicle, which continuously encounters icing problems associated with two other mediums—either land or water *and* the atmosphere. It appeared long ago, therefore, and has proved to be true, that a properly equipped airplane can, with assurance, tackle icing atmospheric conditions substantially in excess of those that could be long tolerated by any other form of transportation.

Early attempts at airplane deicing were intended to lower freezing points or reduce adhesion by the use of applied liquids or pastes, or wicks installed along the leading edges of the aerodynamic surfaces, which would exude various liquids such as glycerin and alcohol. A great step forward in airplane deicing was made by the invention of the Goodrich inflatable deicer boot, which by operation of its stretch areas, as well as the breaking action of its inflatable tubes, caused the ice to break up and be blown away. (See Fig. 13.) This device has been successful with airplanes of modest performance, but, as speeds have increased and wing sections have become progressively thinner, limitations of capacity, disturbances caused by the distortion of the leading-edge shape, and difficulties of preventing lifting of the boot, as well as major problems of maintenance

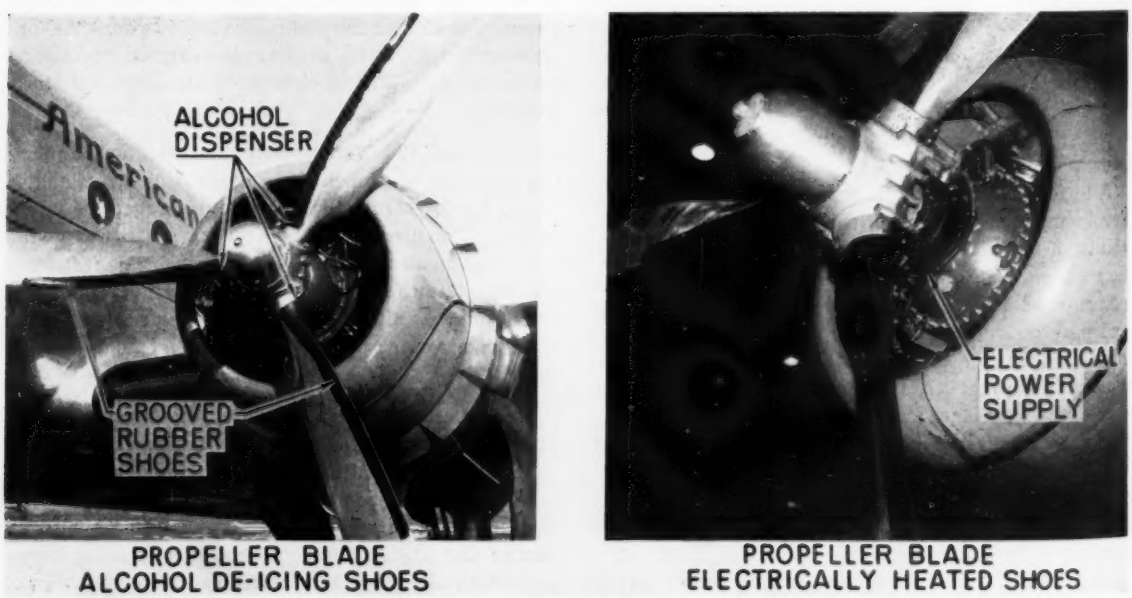


FIG. 14.

R-1830

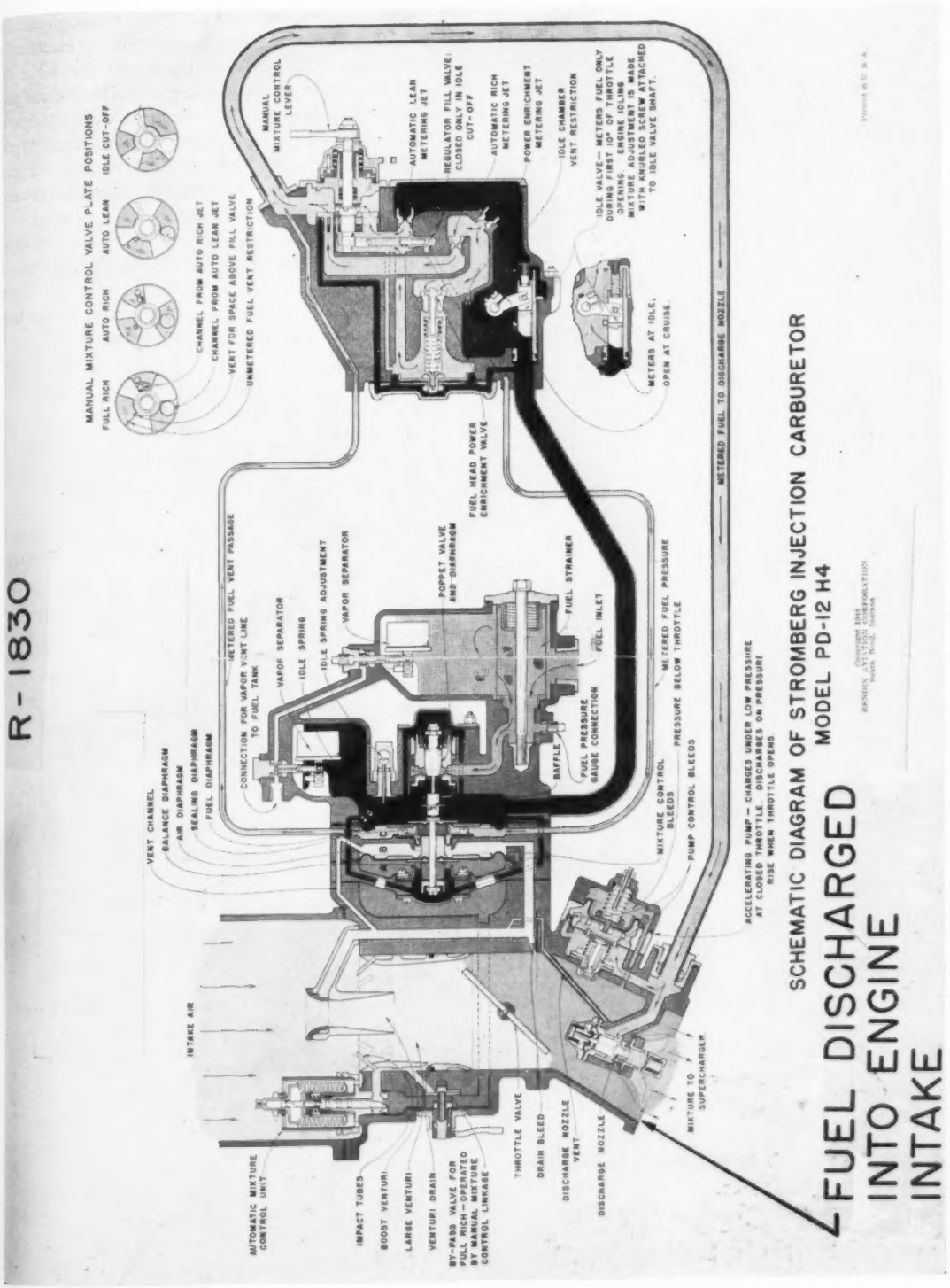

R-1830
SCHEMATIC DIAGRAM OF STROMBERG INJECTION CARBURETOR
MODEL PD-12 H4
FUEL DISCHARGED INTO ENGINE INTAKE
MANUAL MIXTURE CONTROL VALVE PLATE POSITIONS
FULL RICH
AUTO RICH
AUTO LEAN
IDLE CUT-OFF
CHANNEL FROM AUTO RICH JET
CHANNEL FROM AUTO LEAN JET
VENT FOR SPACE ABOVE FILL VALVE
UNMETERED FUEL VENT RESTRICTION
MANUAL MIXTURE CONTROL LEVER
AUTOMATIC LEAN METERING JET
REGULATOR FILL VALVE: CLOSED ONLY IN IDLE CUT-OFF
AUTOMATIC RICH METERING JET
POWER ENRICHMENT METERING JET
IDLE CHAMBER VENT RESTRICTION
IDLE VALVE— METERS FUEL ONLY DURING FIRST 10° OF THROTTLE OPENING. ENGINE IDLING MIXTURE ADJUSTMENT IS MADE WITH KNURLED SCREW ATTACHED TO IDLE VALVE SHAFT.
METERS AT IDLE, OPEN AT CRUISE
METERED FUEL TO DISCHARGE NOZZLE
ACCELERATING PUMP — CHARGES UNDER LOW PRESSURE AT CLOSED THROTTLE. DISCHARGES ON PRESSURE RISE WHEN THROTTLE OPENS
VENT CHANNEL
BALANCE DIAPHRAGM
AIR DIAPHRAGM
SEALING DIAPHRAGM
FUEL DIAPHRAGM
UNMETERED FUEL VENT PASSAGE
CONNECTION FOR VAPOR VENT LINE TO FUEL TANK
VAPOR SEPARATOR
IDLE SPRING
IDLE SPRING ADJUSTMENT
VAPOR SEPARATOR
POPPET VALVE AND DIAPHRAGM
FUEL HEAD POWER ENRICHMENT VALVE
FUEL STRAINER
FUEL INLET
BAFFLE
FUEL PRESSURE GAUGE CONNECTION
METERED FUEL PRESSURE BELOW THROTTLE
MIXTURE CONTROL BLEEDS
PUMP CONTROL BLEEDS
INTAKE AIR
AUTOMATIC MIXTURE CONTROL UNIT
IMPACT TUBES
BOOST VENTURI
LARGE VENTURI
VENTURI DRAIN
BY-PASS VALVE FOR FUEL POSITIONED BY MANUAL MIXTURE CONTROL LINKAGE
THROTTLE VALVE
DRAIN BLEED
DISCHARGE NOZZLE VENT
DISCHARGE NOZZLE
MIXTURE TO SUPERCHARGER

FIG. 15.

and expense, have stimulated the development of new principles. A most important step in the program was the development of heated leading edges for aerodynamic surface deicing, the heat being provided either by secondary air heated by exhaust heaters or by gasoline-burning combustion units. These devices have carried through effectively with the most modern transports, but, as the problem expands with ever increasing speeds and thinner wing sections, there is a trend toward the development of cyclically operated hot air or electrically heated leading edges.

These are a direct outgrowth of the principle ultimately applied with considerable success to the deicing of propeller blades. (See Fig. 14.) The original method was the use of the so-called "slinger ring" from which alcohol was led to grooved shoes on the leading edges of the propeller blades, being distributed by centrifugal force and airflow. These devices were only moderately successful because of the difficulties of securing adequate distribution patterns for the antifreeze liquid and the inability to secure a flow pattern far enough out the blades. The subsequent development of electrically heated leading-edge shoes, or inset units, and the development of the cyclical heating principle, which produced effective deicing with adequate conservation of electrical energy, have produced a successful propeller deicing principle. As stated above, similar principles show promise of successful application to aerodynamic leading edges throughout the airplane.

The deicing of windshields was accomplished originally by the use of externally applied alcohol, sometimes spread and assisted by windshield-wiper operation. More recently and much more effectively, it has been done by the use of electrically heated glass.

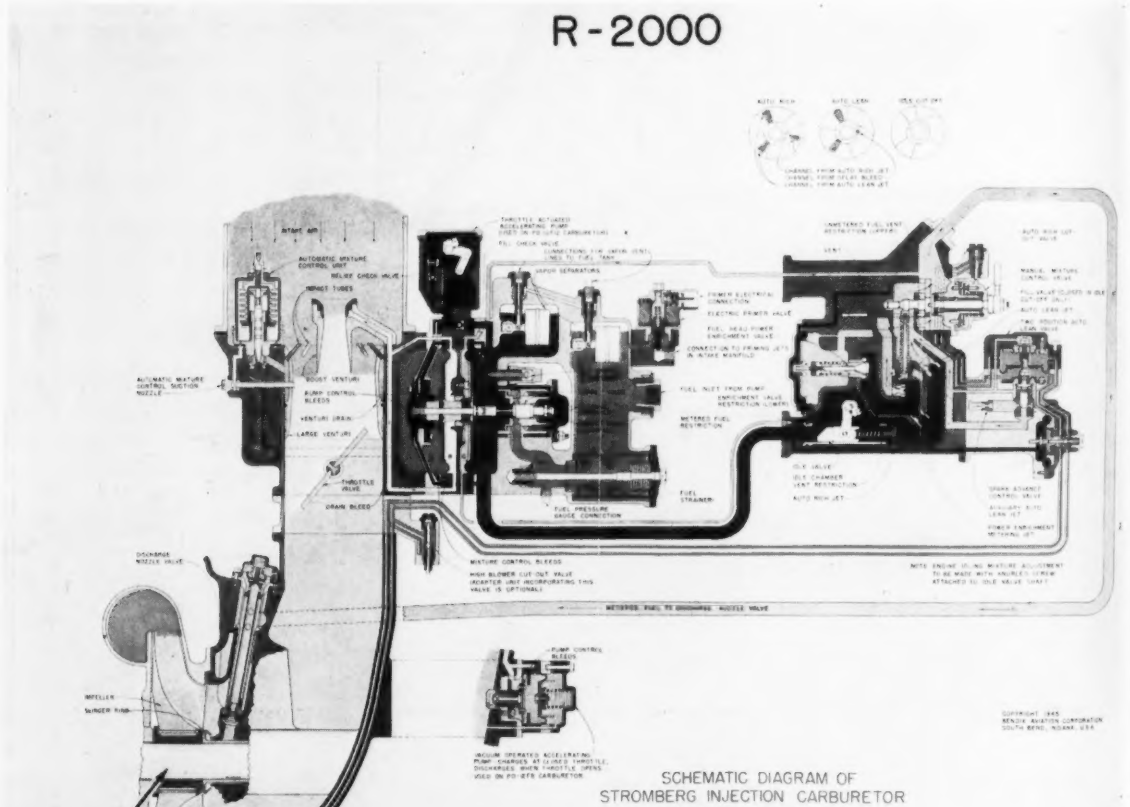
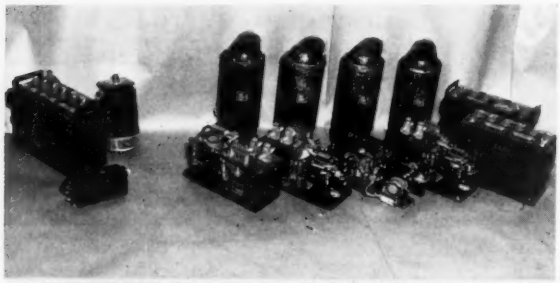


FIG. 16.

FIG. 17.

One of the most important and challenging problems of ice protection has been that of engine-intake and induction-system deicing. The problem was not alone one of atmospheric icing, which affects the intake itself and any screens therein, but was aggravated by the refrigerating effect of the vaporizing fuel. (See Fig. 15.) This problem has been tackled over a long period of time and has been greatly helped by the adoption of so-called spinner injection eliminating the fuel metering and flow in the carburetor itself and substituting air metering only, the fuel being injected immediately at the intake to the engine supercharger where air-pressure heating provides the warm metal parts necessary to help prevent ice formation. Even with this device, an adequate supply of heated air must be provided, as well as emergency alcohol injection to guard against the contingency of power loss due to ice formation making unavailable the necessary heat to correct the icing condition. (See Fig. 16.) Among its other benefits, the use of direct fuel injection in place of carburetion solved the evaporative icing problem for some models of the Wright 3350 engine.

Inertia separators and drains, or shielded intake locations, with or without auxiliary air sources, have been



PILGRIM ELECTRICAL LOAD CENTER	DOUGLAS DC-6 ELECTRICAL LOAD CENTER
1 EACH:	4 EACH:
50 AMP GENERATOR	300 AMP GENERATORS
REGULATOR	REGULATORS
40 AMP HR. BATTERY	2-80 AMP HR. BATTERIES

FIG. 18.

necessary for adequate protection against clogging from snow, ice, or rain of air intakes and vents to the carburetors, tanks, and ventilating systems. Electric heating long ago solved the icing problems associated with pitot heads, static vents, and many other small fixed locations.

One of the problems of surface-heat deicing has always been that of runback and refreezing, which necessitates a careful distribution and proper capacity of heated surfaces of adequate areas. Imperfect protection and obscurity of windshields, either due to ice or heavy rain, have necessitated the provision of satisfactory windshield wipers and openable windshield sectors that permit, under nonpressurized conditions, reasonable side and forward vision without entry of the elements. Deicing of antenna and radomes has been accomplished by electrical heating, by alcohol applications, and by inflatable boots, with varying degrees of success.

DEVELOPMENTS IN LANDING GEARS

This period of transport development also saw the development and adoption of the retractable landing gear and the change from the so-called conventional gear to the tricycle type. (See Fig. 17.) It is difficult today to believe that these ideas should have been rather hard to sell. The mechanical complication and indicated weight of the retractable gear at the speeds then in vogue appeared as serious objections. There was much debate as to the relative drags and economics of streamlined and retractable gears. As speeds and performance requirements increased, however, the retractable gear became an obviously essential feature and was quickly followed by complete flight closure of wheel-well openings. The tricycle gear appeared to have every argument in its favor, except the relatively minor problems of stowing the nose gear, some conjecture as to airplane behavior in the event of nose-wheel failure, and a minor point with respect to the reduction of traction weight on the main wheels when braking. However, the elimination of ground looping as a hazard, the prevention of ballooning on landing, and the benefits of steerability rapidly established the tricycle gear as the best arrangement. One of its incidental advantages was the achievement of horizontal floor conditions on the ground. It did, of course, introduce problems of elevation of rear floor loading height, particularly with the desirable low-wing type of transport.

The swiveling cross-wind landing gear has not found application on any operating transports. It appears to have merit but involves substantial weight and complication, and it has appeared rather unnecessary in view of the excellent ground stability of the tricycle gear and the design cross-wind landing capacity of modern transports.

STICK & WIRE PUSHER

FIG. 19.

OTHER DEVELOPMENTS IN THE AIR-TRANSPORT FIELD

We could go on indefinitely discussing the innumerable air-transport developments that have occurred in the amazingly short period of 25 years. Fuel systems have developed from gravity-flow-type tanks in biplanes and high-wing monoplanes to pump-operated systems. Separate internal tanks have changed generally to integral tanks, with reduced weights and substantially increased volumes and, incidentally, with many growing pains in the form of leakage problems and other headaches. Cell- or liner-type units have come into use for many tank installations.

Electrical systems have gone through a series of transformations from a small battery and generator to larger batteries with a tremendous increase in generator capacities. (See Fig. 18.) Voltage has changed from a basic 12–14 volts to a basic 24–28 volts, and the applications of electricity throughout the airplane have become manifold. Electronic equipment of all types has multiplied greatly in size and number. The trend has included the greatly increased adsorption of electrical instruments, starting equipment, and remotely operated electrical pumps for multitudinous purposes; the wide application of electric controls; the greatly increased lighting loads, both internal and external; and

the generous use of electricity for miscellaneous power, air conditioning, deicing, and buffet services. The net result has been an amazing increase in the use and amount of electrical power.

Hydraulics have developed from scratch to become the frequently used method of power application for the actuation of brakes, flaps, landing-gear retraction, automatic pilot servo operation, power boost to control surfaces, cabin supercharger drives and controls, and many miscellaneous functions such as remote latches, valves, cowl flaps, shutters, etc. Electrical power is often used as an alternate to perform many of these functions.

The general adoption of pressurization in modern transports has been a continuing step in the progress in safety and economy from low-altitude transport operation to the medium altitudes common today. The custom of early years, with no blind-flying instrumentation or knowledge, was hedgehopping, which under low ceiling conditions in mountainous country resulted in not only unpleasant rides but in many fatalities. It was not until the pilots of the early days abandoned the philosophy that their job was to fly the mail and that passengers were a secondary and often undesirable consideration and proceeded to seek higher altitudes of operation for passenger comfort, that the incidence of air sickness started to decline and flying became a reasonably pleasant and safe method of transportation. There was an early reluctance to use any oxygen because of numerous legends concerning its harmful effects. Education in that field, the provision of adequate oxygen equipment and supply, and the development of pressurization have continuously pushed up operating altitudes, with consequent benefit to the traveler in safety, comfort, and speed of service, and with substantial resultant economies to the operator because of more efficient performance, particularly at the longer ranges.

Trends in Structural Materials

The earliest airplanes were built largely of spruce, bamboo, some hardwood, cloth, and wire. (See Fig. 19.) In the event of even a minor crash, they were extremely vulnerable to splintering with deadly effects and, of course, to fire. One characteristic, which was common in the early designs and which will be referred to later in connection with the discussion of possible advantages of different types of airplanes, was the arrangement whereby the pilot, and possibly his passenger, sat foreward with the engine and its heavy equipment behind. In minor crashes, many fatalities resulted from this undesirable distribution of the live load between the concentration of mass and the ground.

These early materials of construction were superseded, see Fig. 20, by welded and fabricated steel structural elements with welded, bolted, riveted, or innumerable patented types of fasteners. The structures were generally doped cloth-covered and, while giving improved strength and crash resistance, were still extremely vulnerable to fire. The all-wooden airplanes of the Fokker and Lockheed type were expensive to build and were beset with major difficulties. There were innumerable problems with fungus growths and rot in conjunction with the glues and woods used. Another problem, which became more apparent later, was the vulnerability to destruction from lightning strikes of airplanes covered with nonconductive sheets. The Faraday cage effect of the all-metal airplane, and even of a tubular structure, gives a substantial protection against the effect of lightning to personnel and equipment within the fuselage and to the fuel tanks and equipment within nacelles and aerodynamic surfaces.

Following the steel and cloth airplanes, there was a growing emphasis on the use of 17ST and other aluminums, with a scattering of magnesium parts, and a negligible but growing use of heat-treated alloy steel forgings and built-up welded units. In due course, there was a wide application of the higher strength 24ST aluminum with increasing uses of heat-treated alloy steels, stainless steels, natural and synthetic rubbers, and many miscellaneous materials. A few aircraft were built almost entirely of stainless steel. The extremely thin sheets necessitated by weight considerations, resulted in a serious loss of stiffness and form retention and presented many fabrication and fastening problems. More recently, use has been made of the even higher strength 75S aluminum, and now titanium for some uses promises increased strengths with weight-savings and other desirable characteristics.

There has been a gradual, but often inadequate, adoption of the different and most suitable materials for specific purposes. The stainless-steel airplanes attempted to use that material for practically everything. It would seem that a more careful analysis of specific requirements and a selection of the best material for each use might well result in significant weightsavings with increased strength, suitability, and durability.

Other Significant Air-Transport Engineering Trends

Time will not permit us to proceed further with a review of the hundreds of significant air-transport engineering developments of the past. We have made no detailed mention of wheels; brakes; tires; oleos; fire-extinguishing systems; hydraulic systems and electrical systems for landing gear, flaps, brakes, and power control; oxygen systems; air-conditioning systems; passenger service elements including seating, berths, lavatories, and food handling and serving arrangements; nor have we referred to the cockpit with its manifold arrangement instruments, and control problems. One of the most important factors we have had to neglect is the examination of airports whose runway lengths and other characteristics are intimately related

FIG. 20.

to significant performance and economic characteristics of our transport aircraft.

The purpose of delineating some of the major factors and referring incompletely to a number of other elements has been, frankly, to impress on you the manifold and complex nature of the problems and the extreme diversification of approaches to their solution. But, out of it all have come significant trends leading toward an amazing uniformity of transport types and arrangements, materials of construction, safety features, performances, and economies. From an examination of a composite modern air transport with its necessary varieties of purpose, we may be able to determine and emphasize some of the still remaining problems of today and indicate additional problems and trends for the future.

In order to examine the possible existence of indicated trends throughout this past period of intensive development, we have plotted certain parameters of American transport aircraft, referring to individual characteristics on a basis of time. Fig. 21 shows the somewhat related characteristics of overall dimensional features such as gross weight, wing span, fuselage length, and fuselage length to wing span ratio. Referring to

the plot of gross weights, it is interesting to note that, despite a rather wide scatter of points, the development has progressed since about 1938 along two clearly defined divergent paths. There has been a constant development with time of larger and larger transport units with obviously longer range capacities and applications. There has also been an underlying development with some increase in size of essentially short-haul transports. Today, of course, the long-haul airplanes are typified by the Lockheed Constellation, the Douglas DC-6, and the Boeing Stratocruiser, varying from approximately 100,000 to 150,000 lbs. in gross weight. The short-haul airplanes are typified by the Consolidated Vultee 240 and 340 and the Martin 404, ranging from 40,000 to 50,000 lbs. in gross weight. We will refer to the significance of this spread in a moment.

The plot of wing span shows a considerable spread of points but indicates a significant average growth in 25 years from about 50 ft. to more than double that value. Fuselage length is also covered by a rather wide scatter of points but again shows a significant increase at a more rapid rate from an average of about 30 to a modern value of more than three times that amount. The rate of increase of fuselage length to wing span ratio is rather interesting in that it indicates some change in aerodynamic proportioning and shows the method by which air-transport capacity has been most logically increased —namely, by increases of fuselage length. The Lockheed Constellation has had some 18 ft. added to its initial length, and the Douglas DC-7 will have had some 12 ft. added. This seems to be a significant thing to keep in mind with respect to future transports. One requirement of a modern contract and specification should be the advanced determination and agreement of a definite plan for capacity growth as power plants of increased size become available in the future. Growth of any individual model in the past has been largely a matter of expediency. Since high-performance aircraft of the future will be limited by Mach drag rise design characteristics, the direction of growth will probably be least in speed and mostly in range and/or capacity. If the airplane is initially planned for a defined operation, the range requirements will be built in from the beginning. Therefore, the normal direction of growth, with increased power or thrust available, will be in the direction of increased capacity. Plans for such a growth program should be incorporated in the initial model so that it can be accomplished with the least expense and trouble.

Fig. 22 indicates some of the trend characteristics with respect to the contents of the fuselage—namely, the crew, passengers, and cargo. Again, the curves are drawn amid a scatter of points, but the trends are somewhat indicative of the probable future. Early crews were one man. The common problem of physiological and psychological reliability of the human being, as well as the parallel question of reliability of a single

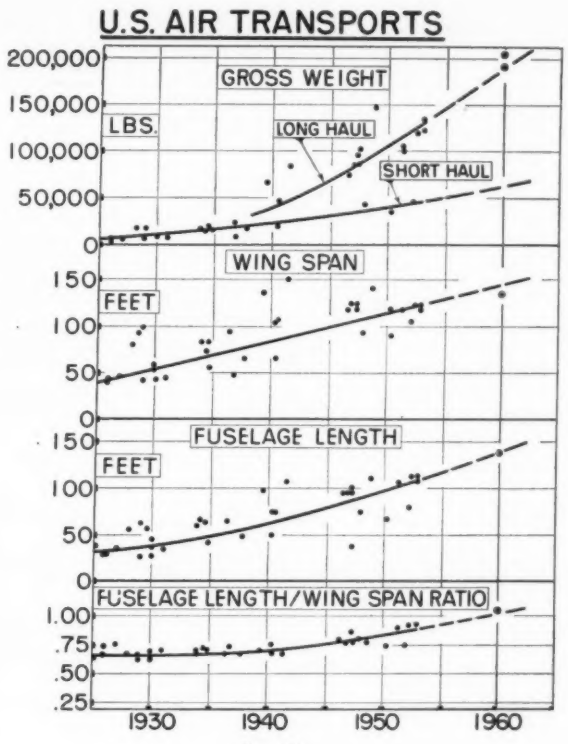


FIG. 21.

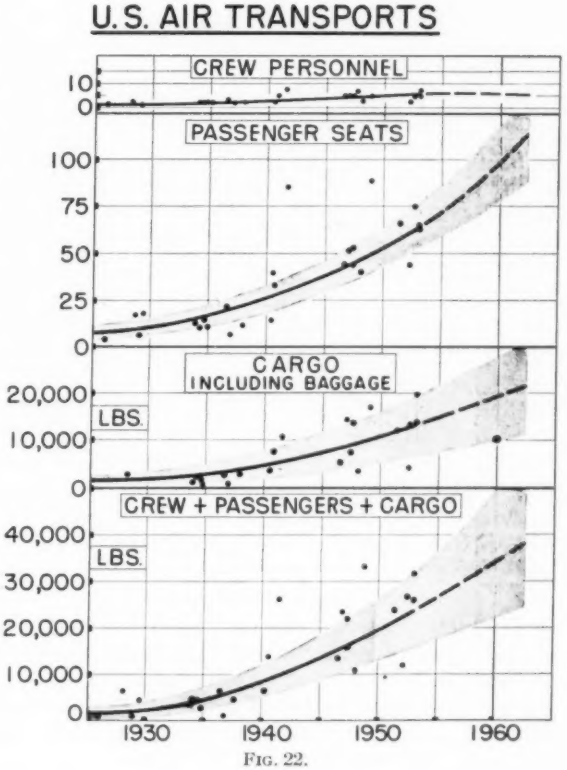


FIG. 22.

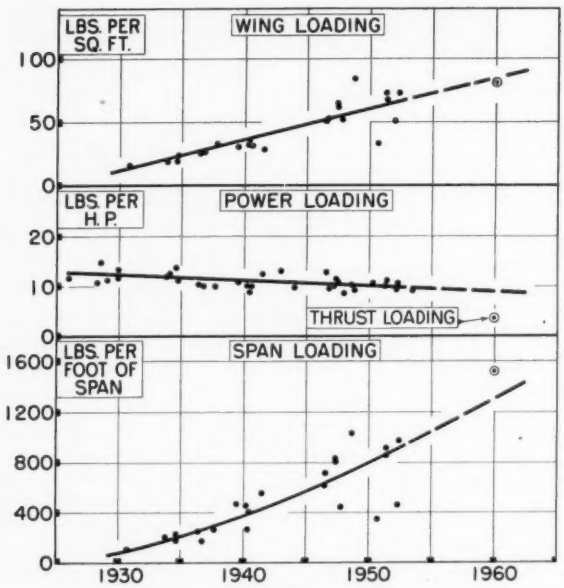


FIG. 23.

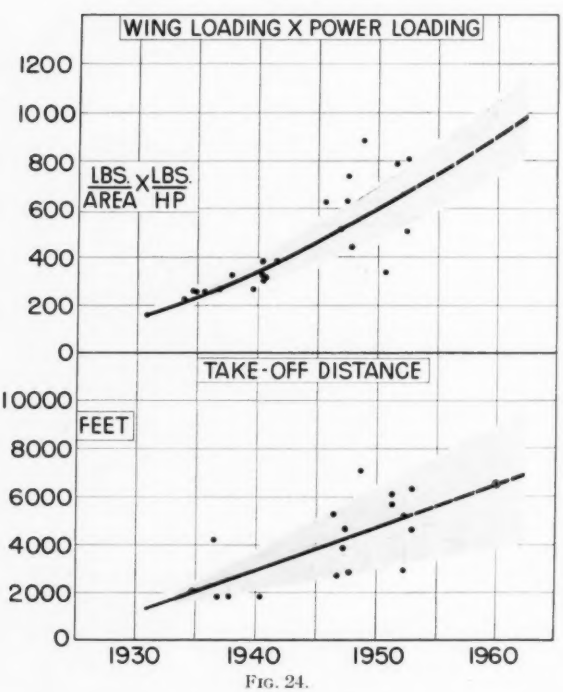


FIG. 24.

power plant, brought about almost simultaneously the early transition to a minimum flight crew of two, as well as a minimum power-plant arrangement of the same number. It might be considered that the initial cockpit crew of two was frequently one and one-half rather than two, since it was not uncommon in the early days for the pilot to take the same attitude toward an additional member in the cockpit as he did toward the existence of the passengers in the cabin! Both were tolerated to varying degrees! This was just a phase, however, and well trained and coordinated crews of two became the operating minimum. Crew growth thereafter was in consideration of additional segregated functions to be performed. As the needs of the passengers became evident, cabin crews were added, and as the needs of the cockpits and their manifold equipment became apparent in the larger airplanes, flight engineers were added. For the largest airplanes multiple cabin crews are necessary to perform the quantity of tasks required, and for some uses of the airplane, particularly long-range overwater operations, some arrangements of equipment and functions indicate the need for radio operators and navigators. For those flights planned to exceed desirable or legal time limits, partial or total reserve crews are carried. The crew number factor, of course, has shown a rising indication with the years, but determinations for the future should depend entirely on functional analysis of the overall number of segregated jobs to be performed and proper considerations of the relationship of flight time to the physical and mental fatigue of the tasks involved. Obviously, it is a prime duty of design and air-line engineers continuously to simplify the tasks so that more can be accomplished with less total effort and with improved safety and efficiency.

The time curves of passenger seats, cargo, and the total of all loads show the accelerating upsweep of required capacities with time. This is interesting in its indication of the exponential growth of the industry. I think it is generally agreed that, at any given time and under any given set of operating conditions, an operator would be wise to keep his airplanes a little on the small side of maximum required capacity. A study and report prepared in 1930, using the sum total of available statistics from the extremely diversified American Airways operations of that time, indicated that, with the then scattered demand and unreliability of operation, more than 90 per cent of the business could have been accomplished with aircraft of less than half the average size of those then operated. The indications led one of the most thoughtful and intelligent early leaders of air transportation to a conclusion that a 50 per cent load factor was the most that air transportation could ever hope for. How untrue this was has been demonstrated conclusively as air transportation achieved adequate utility and reliability. However, to contemplate that the extremely high load factors of today can be continuously maintained for future periods of possibly greater economic stringency would appear to be on the side of recklessness.

This period has recently seen the development of the so-called coach or air tourist services—with somewhat reduced and simplified accommodations handling more passengers per airplane at lowered rates—made possible by the flexible nature of the equipment.

With the relative inflexibility of the larger size, high-performance transport units of the future, it would ap-

pear desirable to arrive at a basic determination of a satisfactory and fully acceptable standard of service and to determine at what rate such services can be sold to develop the maximum economic possibilities of that type of airplane. If there is economic justification for airplanes of such sizes and performances in a sufficient number of services, they will be built and successfully operated. If not, the industry would be well advised to move slowly into the high-performance possibilities of the future. There is no reason to be pessimistic about the situation, for studies, to date, appear to establish that such airplanes can be developed in sizes fully consistent with anticipated capacity requirements and that in such sizes they can operate at reasonable load factors and give the desired high performances with economic success.

Speed has many values, both direct and indirect, for which some compensation should be reasonably expected. To design these future aircraft, however, without taking full advantage of the economic possibilities and without planning the future growth programs of the aircraft would be inexcusable in view of the tremendous risks in development and capital investment required.

The curves of wing loading, power loading and span loading (Fig. 23) with time show the principal results of continually improved economic weight factors, performances, and efficiencies. Coincident with the developments of high lift devices, the increased wing and span loadings and lowered power loadings have made possible the economically efficient transports of today. The removal of the arbitrary 80 m.p.h. stall speed limitation cleared the path for achieving the benefits of these technical developments.

The curve (Fig. 24) showing the product of wing loading × power loading against time serves as a basis for the significant curve of runway length requirement with time. It must not and need not show a continuing increase with time. Transport designs must be geared to reasonable and practical runway-length requirements.

Referring to Fig. 25 of trends of performance characteristics, the maximum speed increase has been almost constant with time since the beginning of powered flight. It has been frequently pointed out that, until the advent of the jet, maximum military speeds had increased at an almost flat rate of 14 m.p.h. per year, while transport top speeds were going up at about half that rate. As the curve shows, cruising speed increases have tended to increase a little more rapidly with time, primarily, I believe, because of the development of engine reliability and the ability to use higher percentages of cruising power.

The service ceiling scatter of points is naturally wide and merely shows an indication of the increasing altitude capacities of power plants, the tendency toward lower power loadings with the higher wing loadings, and the incorporation of more adequate power performance reserves with time.

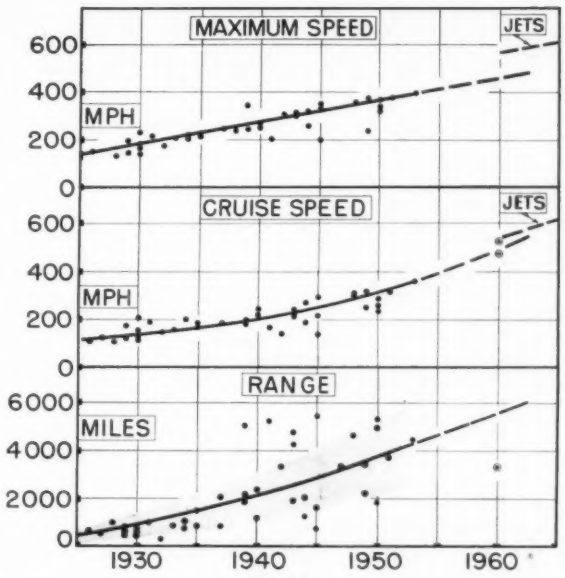


FIG. 25.

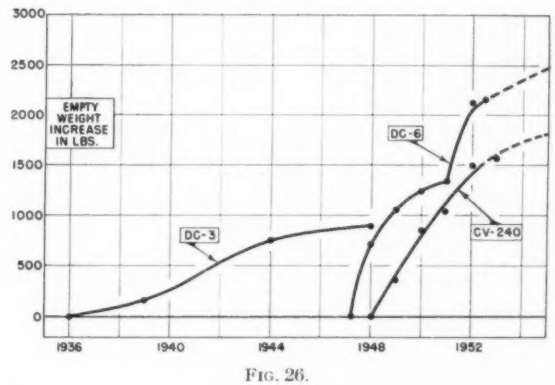


FIG. 26.

In the future, as increasing emphasis is laid on speed and since the speed must be attained at high altitudes and by the use of relatively large powers or thrusts, service ceilings will, I am sure, continue to increase.

Ranges are a function of the service pattern requirements of the operator and a measure of the ability of the design engineers to meet the desired figures. High aerodynamic efficiencies and low specific fuel consumptions are, of course, the basic requirements for maximum ranges. Both these factors have played an important part in the rising trend shown. There is, of course, for every airplane a minimum range below which its space capacity makes the airplane inefficient because it cannot use its full weight ability. At the other end of the scale, there is a maximum range where the combination of fuel and pay load uses up all the weight capacity of the airplane and beyond which its economic utility deteriorates with extreme rapidity. It is foolish to contemplate that this maximum range, as normally stated for a new airplane, is a realistic value.

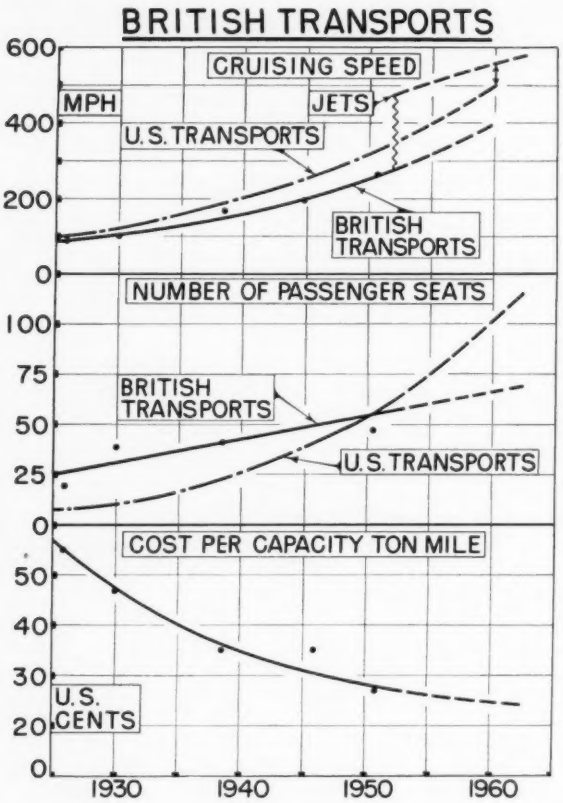


FIG. 27.

The inevitable service increases of empty weight—always a maximum in the early period of operation and happily decreasing with time—demand a sensible correction factor to determine the realistic maximum range for practical operation. (See Fig. 26).

There is also a tendency on the part of design engineers to minimize the operational reserve fuel requirements and other essential factors that cut into range pay load. The power-plant manufacturers have often been unduly optimistic with respect to the fuel consumptions to be realized in operation, which has a most significant bearing on range capacities. In the past, there have also been significant variants with respect to realized speed performances because of a disregard of the drag penalties invoked by the necessary application of external antenna, radomes, deicer boots, and similar parasites.

Most fortunately and with increasing urgency as speeds increase, much is being done to provide satisfactory antenna arrangements completely submerged within the contours of the airplane. Many problems of satisfactory functional performance still remain, and new icing problems of unknown magnitude will be introduced. These include possible losses in transmission and receiving efficiencies, beam distortion, and problems of lightning strikes, which with nonconductive areas give some reason for concern. Possible losses of structural strength in flush antenna areas may also aggravate problems of bird or hail strikes.

Comparison of British with American Transport Operation

As an interesting comparison, I should like to show, at this time, a plot of British trends in transport operation for the past 25 years, prepared from data taken from Peter Masefield's Brancker Memorial Lecture of 1951. (See Fig. 27.) Cruising speeds in 1925 started at about the same value—100 m.p.h. or slightly below—but by 1952, American cruising speeds were well above 300 m.p.h., with 360 m.p.h. promised for 1953; while the British, with conventional engines, have stayed at a conservative 260 m.p.h., with an indicated projection to 275 m.p.h. or thereabouts by 1953. It would appear that in the past the British have not been nearly so interested in speed as have we Americans, which seems natural in consideration of the shorter British European Airways (B.E.A.) cruising distances involved. The benefits to be achieved in block speed made good are so much a function of range that speed greatly loses its significance in the shorter range operations. Mr. Masefield pointed out that, while London–Paris (about 200 miles) cruising speeds had increased some 225 per cent in 20 years, only about 35 per cent increase in sta-

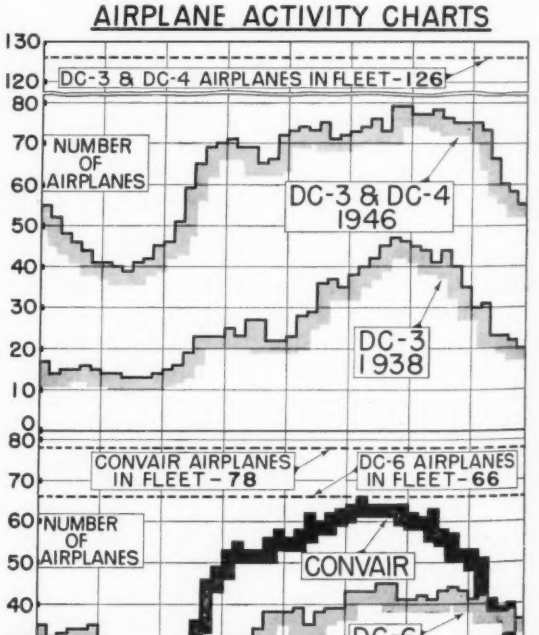


FIG. 28.

tion-to-station effective speed was realized. This consideration must be kept prominently in mind by local operators evaluating the questionable benefits of substantial speed increases in short-range operations. Of course, in 1952, the British made a cruising speed jump to some 450 m.p.h. or better by the introduction of the Comet jet operations and will proceed to do even better in the future as larger power plants are applied.

The B.E.A. curve of average transport passenger seat capacities is also interesting in comparison with the American trend. Starting with very nearly the same values in 1925, the British capacities rose rapidly and then flattened off by 1952 to an average maximum of some 47 seats, while the American curve has increased at an accelerated rate to a comparable average of about 65 in 1952.

The cost curve of British operation has had a healthy downswing through the years, although it is difficult to attribute too much significance to the absolute values since the numerous reorganizations and somewhat uncertain conditions with respect to subsidies have made determinations of cost rather indefinite. The same may be said of the determinations of American costs in the past, which have been greatly confused by ill-defined and variable accounting systems and by considerable uncertainty as to the nature of rewards in the subsidy and compensatory classes.

Range of Operation of A. A. Fleet

Fig. 28, entitled "Airplane Activity Chart," emphasizes a change in the nature of transport operations with time and is built up from the numbers of airplanes in operation at any hour of the day or night in American Airlines. You will note that in 1938 when we were operating DC-3's for all types of service—long, medium, and short—to the extent of their range capacities; we made well-distributed use of the airplanes, with the most airplanes in the air during the daylight hours of maximum traffic consumption—namely, late afternoon. If we look at 1946, the chart shows a substantially greater fleet composed of DC-3's and DC-4's. The average range of operation has gone up by the inclusion of the larger DC-4 airplanes, but we still show the same maximum activity throughout daylight hours, somewhat leveled off during this period with a substantial relative decline during the early morning hours. Now, if you will look at the present American Airlines' fleet of 78 Convairs and 66 DC-6's, you will note that the type of operation has been segregated into essentially long-range operations for the DC-6's and short range for the Convairs. The DC-6 curve, by this specialized application, has substantially leveled out throughout the entire 24 hours—a most efficient utilization of equipment in that respect and probably one of the substantial reasons why DC-6's costs per unit mile show such a favorable value. On the other hand, you will

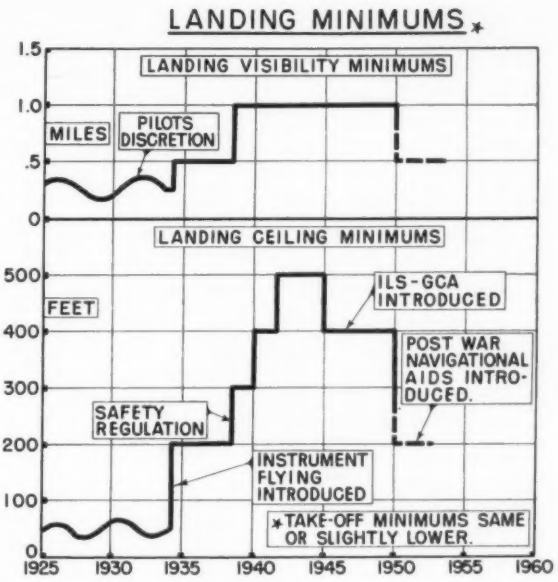


Fig. 29.

note that the Convair, assigned primarily to short ranges of operation in local services, has an extremely high utilization throughout the daylight hours but falls to extremely low values and even to zero for one time in the early morning hours. The fleet required to perform the daylight services is, obviously, large, but an equal number of airplanes are sitting on the ground unused for a portion of the night. This is one of the factors that contribute greatly to the apparently high unit operating costs of the short-range units of such a combined fleet. Studies of this kind are revealing and tend to offset some of the erroneous impressions that frequently prevail with respect to the relative economic merits of aircraft. The nature and efficiency of application is just as important as the performance and associated characteristics in studying transport airplane economics.

You may also be interested in a quick glance at another plot. Fig. 29 is a correlation between landing minimums and time affected throughout the period by numerous influences and fortunately showing marked and continuous improvement since 1945. This is one of the essential factors in the ambitious objective of some day achieving 100 per cent operating factor. It is, I think, a pretty good confirmation of my earlier statement, that as a type of vehicle the airplane will eventually accommodate itself better to adverse weather conditions than any other type of transportation.

You might also like to take a glance at the interesting increases in air-line engine overhaul times (Fig. 30) from 1939 to date. If we were to project this curve further back, we would find it starting at 100–300 hours per overhaul in 1930. This experience should not be dissimilar to that which will, in the future, probably be achieved by jet and turboprop power plants. It is a

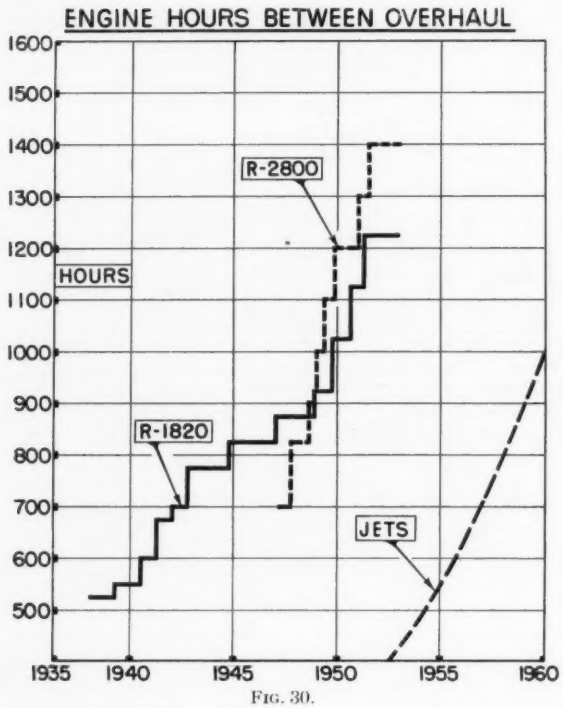


FIG. 30.

history of the progressive improvement of engineering design, materials, testing, and operating techniques which has always accompanied the development of power plants. There seems no reason for a change in principle in the future. Let us be reasonably optimistic.

AIR TRANSPORTS TODAY

With the tremendously diversified background which we have been discussing, it seems strange that we have come to this point in air transportation with an almost firmly established type of aircraft and with startling similarities in power plants, cockpits, and installations of all kinds. The reasons for this, of course, include the concentration of basic information in nationally available laboratories, notably the N.A.C.A.; the centralization of procurement in the Navy and the Air Force, the two largest customers for aviation development projects; and the establishment of uniform regulations and supervision for the design, construction, testing, and operation of commercial aircraft under the C.A.A. and the C.A.B. Within these influences, there has been a substantial latitude of development, but they have contributed greatly to the bringing about of a fairly uniform air-transport product. I would mention modestly that air-line engineers have, to some extent, played a part in the same program in determining and emphasizing the important technical needs of their industry.

There are, of course, substantial variations in size, speed, range, number and rating of power plants, weight and space capacities, and many other features, but if we were to define the modern American air transport, and it does not appear to be dissimilar from many of the good transports developed and used abroad alongside of the American products—it would be a low-wing, all-metal, internally braced, smooth stressed-skin structure with two or four conventional engines driving constant-speed, full-feathering, reversible propellers. It would be fitted with retractable tricyclic landing gear with various numbers of wheels and brakes dependent on the size of the airplane. The streamlined engine housings or nacelles would in flight effect complete closure over the retacted main wheels. The airplane would have slotted flaps, and the ailerons and tail control surfaces would probably be tab-trimmed or -controlled and would be metal-covered. The cockpit would be fitted for a minimum crew of two, with at least one more for the large four-engined types, and would contain somewhat standardized communication, navigation, and control equipment of many types. For the medium and longer ranges, the entire fuselage would be pressurized, tended by a suitable cabin crew, and fitted with comfortable reclining seats, lavatories, and suitable food accommodations. The airplane, power plants, and propellers, etc., would be fitted with ice protection, generally of the heat type. Numerous details, standardized in nature, could be appended to this list, but the above would describe, in general terms, any and all of the current brood of operating transport airplanes.

But with all this indicated standardization and excellence, there remains much to be accomplished in the engineering field, in addition to the pleasant contemplation of such fundamental changes as those to turboprop or turbojet types and greatly enhanced performance characteristics.

LOW-WING VERSUS HIGH-WING AIRCRAFT

I sincerely hope the future holds no threat of change in basic type from the essentially low- or mid-wing all-metal landplane. Innumerable studies have been made, and from time to time proposals are made suggesting high-wing transport designs—a type that was fairly common 20 years ago. There are two popular arguments in favor of high-wing airplanes. One is that the passengers can see the ground better, and the other is that the floor is closer to the ground and, therefore, the airplane is easier to load and unload. These advantages are real, but their value does not begin to balance the passenger safety and economic advantages of the low-wing type. Every thoroughly honest, comparative study with which I am familiar has shown some weight advantage in favor of the low-wing, primarily because of the shortened landing gear and the elimination of keel and supplementary structure necessary to achieve the minimum required fuselage strength forward. But, the irrefutable advantage of low- or mid-wing design lies in the area of safety. As stated earlier in the lecture, the

NIGHT LANDING IN APPLE ORCHARD
OVERSHOOT - AIRPLANE STOPPED BY DIKE AT FIELD BOUNDARY
LANDING IN TREES
OVERSHOOT - AIRPLANE STOPPED BY LEVEE AT FIELD BOUNDARY
ENGINE FAILURE AT TAKE-OFF STEEP 6 FOOT RISE AT EDGE OF FIELD.

FIG. 31.

disposition of live load, if we may refer so casually to our passengers, between the mass concentration of engine, wing, and fuel weight and the probable point of impact with the ground in the event of a crash landing is almost certain to result in aggravated casualties. Figs. 31 and 32 illustrate 100 per cent survival accidents to emphasize this point, and we could produce literally dozens of pictures of actual incidents in which this has been a most significant factor. It is apparent that one of the best ways to absorb the energy of impact is to permit the destruction of structure. How much better it is to have that structure not the fuselage in which the passengers are housed but rather the wings and engine installations! One only needs to recall the repeated experiences of the war to emphasize this and the great difficulty, if not impossibility, of executing satisfactory

FIG. 32.

ditching operations with a high-wing type of airplane. May I, therefore, repeat my sincere hope that this great step forward in safety be recognized as an established trend and that no retreat from it be made.

CRASH SURVIVAL

Another most significant factor in crash survival is the engineering of proper arrangement and detail with respect to the passenger- and crew-occupied areas. A great deal of work has been done in this field to determine the nature of the loads and their significance with respect to personal injury. It does not seem too ambitious to expect that a well-designed and -fitted airplane would readily permit its human occupants to survive a 25*g* crash, probably more than can normally be taken in most vehicles without serious injury or death. It seems to me that the basic approach to the problem should be from the point of view of the capacity of the human body to endure stress, when properly supported, without serious injury or death. Investigation has shown that distributed stress has permitted up to 100*g* without fatality in numerous cases of accidental or suicidal falls. Innumerable tests of properly supported subjects have been conducted at 30–40*g* decelerations without injury. These, then, should be ultimate design objectives for safety in aviation crashes. The basic nature of aircraft structure is such that, by its very destruction, substantial impact energy can be absorbed. With reasonable energy-absorbing seat mountings, chair structures, and seat belts and the elimination of extraneous hazards that result from personal impacts against hard or sharp objects or damage from flying missiles, it is not difficult to see many ways in which aircraft crash safety can be made superior to any other.

It seems unnecessary to comment that static strength requirements of chairs, even with a recognition of the need for strength tests of varying amounts in all directions, could be met by an airplane chair designed and built of a brittle material such as glass! The inappropriateness of such action hardly needs comment, but the inadequacy of the requirements as an expression of the needs to meet the impact loading anticipated is evident. A reasonable deflection of seat structure under severe impact load must be permitted. On the other hand, to develop serious distortion or display inadequate retention to the basic airplane structure will result in an unsafe cabin condition due to the interferences with emergency evacuation. These hazards are recognized and methods of solution have been proposed. There does not seem to be any reason why suitable engineering action should not be taken.

Another most significant aspect of passenger cabin safety is that associated with the provisions for ingress and egress—most important in event of emergency. Undue emphasis, by regulation, on the aft location of

major emergency exits does not appear to be a suitable recognition of the overall picture. An insufficient amount of statistical data does not justify a conclusion contradicted by actual experiences that airplanes terminate crash landings facing forward. Actually, they end up with their axes at all angles with the line of initial impact from zero to 180°. The substantial evidence to that effect seems to emphasize the essentiality of treating the airplane, right and left and fore and aft, with due regard to required locations of standard and emergency exits. It is the writer's strong opinion that the normal entry door or doors to the cabin rate many times the value of any other exit in emergency because of familiarity as to location and use. It is true that the aft end of the fuselage is often the least damaged in a crash, but this is not so to an extent that justifies an abnormal or exclusive emphasis on that location for emergency exit purposes.

It is also unfortunate that consideration of emergency exit locations has placed undue emphasis on the forward inertia and pressure ejection of fuel from ruptured tanks. With the variable final position of the aircraft axis as one factor, the existence of reasonably strong prevailing winds may completely nullify the effects of any forward jettisoning action of the fuel. Even if the airplane proceeds in a straight line, as the fuel spills from the ruptured tanks, the nose of the airplane frequently passes over and beyond any fuel, which may end up under the rear of the fuselage or on either side. The plea, then, is for a complete adequacy and universality of treatment in this respect.

I would also like to open the strong case for standardized and improved locations, designs, directions of opening and hinging, and types of latches, handles, and operating instructions for passenger doors of all descriptions. In my opinion, this factor is as fundamental to evacuation safety as any other consideration. The entire question of emergency evacuation merits much thought and engineering study.

Engineering thinking must also recognize the impossibility of service mechanics, no matter how intelligent, coping adequately with the unknown. It cannot be assumed that a service mechanic always has at his elbow a Maintenance Manual, even if it were complete in all details, nor does he have the time or inclination to look up every subject that may be remotely related to his particular problem. There have been many instances of mechanics unwittingly drilling through a blind floor or bulkhead into a congested mass of unprotected electrical cables or conduit. A little forethought would indicate that the airplane should be marked in such a way that, without reference to a Manual, the mechanic would have known that behind any critical location on a floor or bulkhead there were items of equipment or installations which made it inadvisable, at least, to drill through. This type of advance engineering thinking is the only guaranteed preventive of innumerable accidents and mishaps.

All too often details of thoughtless design or installation engineering are discovered as the causes of incidents and accidents, both minor and serious—sometimes inadequate designs that you would expect to find in a child's toy rather than in a million-dollar product like a transport airplane—hinge pins that fall out; latches that become inoperative and unlatch; leading-edge covers that hinge on the wrong side and come dangerously loose in flight; and, in the less dangerous but equally annoying and expensive area, faucets that will not shut off; outboard drains that freeze; valves and controls that lock from low temperatures; equipment items that come loose in turbulence and make dangerous missiles. These are a few among literally hundreds of details that challenge the quality and capacity of air-transport design engineering, and we must keep them constantly in mind so that the next series of products, some indicated to be in the multimillion-dollar class, will be in all respects worthy engineering products of the highest quality.

This leads directly to a thought I would like to express concerning the place and importance of safety engineering in an aircraft engineering organization. Some feel that safety is of such universal concern that its principles should be taught and inculcated in all aircraft engineers—and that is all. Others feel that safety should be a separate engineering function responsible to a rather high executive in the organization—something like *Inspection*, or to a lesser degree *Weight Control*. I think both approaches are of the utmost importance. There is no equivalent to continuously conceived and originally built-in safety design features; but, recognizing the effects of continuously present pressures that are adverse to a quiet and thorough contemplation of safety in design, there is also no substitute for a constructively critical review of all design from the safety experts' point of view. We have not done it adequately—let's do it!

High-Performance Aircraft of the Future

Now, assuming that we have defined our modern transport type and by imaginative analytical engineering have improved its quality, let us examine a few of the problems facing the next series of high-performance aircraft when they come into being. It does not seem improper to conclude that the industry would prefer to tread on the firmer ground of relatively conservative increases in performance and size, not achievable in the larger transports with any reciprocating engines that are planned or likely but certainly attainable with many advantages by the use of proper size and efficient turbopropeller-type power plants when available. However, it is obvious that there are many technical problems in such a satisfactory development, even beyond those incidental to the early satisfactory operation of jets. The great emphasis which the military program has placed on jet development will unquestionably

bring that simpler type of power plant to an adequately satisfactory and reliable condition long before we can hope to have turbopropeller operations. There appears to be in the American domestic picture a bracket of required ranges—roughly from 500 to 2,500 miles—and appropriate sizes of well-developed jets to give a reasonable and efficient transport airplane of high performance and satisfactory economy. Below these bracketed ranges and above them, there would still appear to be an eventual great need for the application of turbopropeller power plants.

From the point of view of any air line, even the largest it is obviously undesirable to operate any more models of aircraft than are necessary to perform the required services. The smaller air lines may well hope to continue to do all their work with one model. However, in the domestic industry as a whole and particularly among the larger air lines, it seems that a minimum of two models will be required, continuing the trends of the indicated split in developmental types and characteristics which originated some 15 years ago in America with the concept of the DC-4E.

Encroaching on the absolute minimum of aviation ranges, the helicopter will eventually find its economic niche. It is my opinion, however, that the inherent mechanical complexity of this type of flying machine, despite its apparently desirable characteristics for short-range operation in congested areas and its basic principle that requires such a large proportion of its power for sustaining it in flight, will continue to make the units extremely expensive in first cost, relatively expensive in operating cost per unit mile, and fraught with problems of dependability. Furthermore, if they are to be operated in the congested areas proposed, we must not forget that they are dependent on power-plant reliability as is an airplane and have many unsolved problems of stability and controllability, particularly under instrument conditions. The single-engined-single-pilot transport airplane went out of vogue many years ago, and we must question the safety factors of such a helicopter operation. Any evidence to the contrary is based on a limited operational experience. Yet, we blithely accept the idea that helicopters can safely operate over congested built-up areas. There is nothing in the above to disparage the usefulness or eventual promise of the helicopter as a lifting and carrying device, but it must be properly applied just as must the airplane.

There is much discussion in the local operations field concerning the specifications for a desirable and efficient small transport airplane, which will presumably improve vastly on the economy of the DC-3. Its engineering characteristics would, presumably, not be too much different. It might be expected to operate with a little less field requirement and might be expected to have somewhat better single-engined performance and reserve. It might have somewhat better flying qualities. It would need little, if any, more in the way of speed or altitude performance to accomplish its intended purposes, but it must do all these things and be much more economic per unit mile. The approach appears to be a suggested increase in capacity, which with a constant assumed load factor indicates, at the same or slightly decreased costs per airplane mile, greatly decreased costs per unit mile. The fallacy of this appears to be in the assumption that local operators can establish and maintain a high load factor. As previously mentioned, an engineering economic study made for American Airways in 1930 emphasized the startling conclusion that about 90 per cent of the business at that time could have been accomplished with airplanes less than half the size in operation! There does not seem to be too much difference in many of the characteristics of local operations today and tomorrow compared with the scattered operations of American Airways in 1930, and, if that comparison be in any sense legitimate, it would seem to emphasize that the cost per airplane mile is a much more important factor than indicated cost per unit load mile achieved by increased size and possibly excess capacity. It would be interesting to consider the results that might be obtained if it were physically possible to expand the width of a DC-3 airplane the necessary foot or so required to provide it with a satisfactory additional row of seats, raising its capacity from some 24 to 32. The changes, if efficiently accomplished and accompanied by some supplementary cleaning up of the airplane as a whole, would, I am sure, have a relatively small effect on the performance or cost per mile of the airplane. In its effective results, it would produce the approximate equivalent of some airplanes proposed for local operations. It might or might not achieve a substantial increase in passengers carried, and, if it did not, it would achieve no economic benefit. I think increased scheduled services and improved dependability are much more important factors for local operations. I doubt if pressurization is generally necessary or economically justifiable.

In the larger domestic air-line picture it appears highly desirable to endeavor to perform the services needed with a continuation of development and reasonable growth in the two general types now in use—exemplified on the one hand by the Stratocruiser, Constellation, and DC-6 in medium- to long-range operations and, on the other hand, by the Convair 240 and 340 and Martin 40-4 for the shorter ranges of operation. Since, with the shorter range aircraft, the field requirements are so important and the benefits of altitude and speed cannot be effectively realized, it would appear that a logical development would lead eventually to the turboprop type. This picture is so hazy because of the unavailability of adequately proved or suitable power plants and associated units that we cannot discuss it sensibly, except to point out that the same general engineering design comments to be later

referred to apply equally to eventual developments in this field.

With respect to the medium- and long-range domestic aircraft, however, it is fairly clear that reasonable increases of size, coupled with the economic benefits to be achieved from high-altitude high-speed operation, can permit the reasonably early development of such transports built around adequately proved and efficient jet power plants, Fig. 10. As in the past, the design starts around an acceptable number—in this case four—power plants of an adequately efficient and reliable type, with suitable horsepower or thrust producing ratings. From this platform one can entertain variables in range, capacity, and speed. Ranges are, of course, dependent on the minimum and maximum desirable or required distance characteristics of the operating air line. Capacities and speeds thereupon become the principal variables, coupled of course, with innumerable concepts of arrangement and functional characteristics.

With jet-type power plants the necessity for transport performance at reasonably high altitudes and high subsonic Mach Numbers becomes apparent. Drag rise characteristics dictating maximum speeds, directly influence the selection of wing thickness ratios and sweepback, and with the basic selection of power-plant location and arrangement, the airplane begins to take form. Rather intricate studies involving assumed variations of performance and capacity lead eventually to a determination of the best compromises and a firm definition of the airplane. Frankly, this is the process that has been going on for many months—the final determination is, of course, the analysis of operating costs based, to some extent, on first costs including development and leading to a decision both on the part of the manufacturer and his prospective customers as to whether the project should proceed.

The Noise Problem

Many other considerations are involved in such a decision. We are currently faced with a serious transport noise problem. It is not that which has affected the relationship with the occupants of the airplane fuselage, which has been reasonably solved to date and can certainly be handled in the future by known techniques even with the disturbing noises emanating from jets. Reasonable further application of the same principles as in the past—namely, shielding, reflection, isolation, insulation, and arrangement—can handle that problem. The so-called noise problem of today is that which lies between the power plants and equipment on or in the vicinity of the ground and the people in the neighborhood. The problem is being tackled on many fronts, and practical improvements have already been made in the nature of operational controls as to directions and altitudes of take-offs, climb-outs, approaches, and landings. Baffles and directional reflectors and absorbers are coming into use to control some fixed ground run-up problems. It has become evident that the problem is not strictly one of noise but has substantial elements of individual and mass reactions to fear and various annoyances. People have indicated their great concern about noise and low flying in general and have registered innumerable specific complaints of interruption of sleep, fear of crashes, annoying vibrations and rattling of dishes, interruptions of radio and TV programs, interruptions of telephone conversations, and concern about frightened children. We can certainly not deny the existence or legitimacy of this most serious problem. While we are gravely concerned about the generation with large reciprocating engines of overall maximum sound intensities of 100 to 105 db., and with conventional propellers of 115 to 120 db., we must look forward with even greater concern to the possible development with supersonic propellers of sound intensities approaching 130 db., and with unaugmented turbojets of 125 db. rising to perhaps 140 db. with afterburners. These values are well beyond acceptable levels and threaten to reach proportions that we cannot hope to control satisfactorily by the simple expedient of operational restrictions. It is absurd to suggest that a reasonable solution would be the relocation of airports or time limitations on their use. The penalties and depreciation of military and commercial values attendant on such a solution would work a totally unjustifiable disservice to the national interest. We must, therefore, consider the problem one of the most difficult but inspiring challenges to be thrown at the scientists, engineers, and operators of the country. It has been disappointing to find the degree of pessimism prevailing among the scientists and engineers on this subject. However, the seriousness of the problem challenges us to a full re-examination of the basic principles of sound generation, propagation, and control. It further demands an investigation and analysis of phenomena which may be directed toward the solution of the problem once their nature and significance is understood. It has been stated that noise is an unavoidable accompaniment of the generation of power or thrust and its application in the atmosphere. Nevertheless, we have such contradictory observations as that of two jets, the larger of which develops the lesser noise and apparently evokes fewer complaints. We also have the encouraging thought that sound represents lost energy even though it be small in percentage and magnitude. Efficiency gains, in some cases can accompany sound reductions, and that hope should give an added stimulation to the program. We also know that the harnessing of exhaust energy by the operation of exhaust turbines, as in a compound engine, will make a reduction in the exhaust noise. We also know that reduction of propeller tip speeds, with negligible loss of efficiency, although involving some weight penalties, produces marked benefits in noise reduction. We know, further, that turboprop installations such as

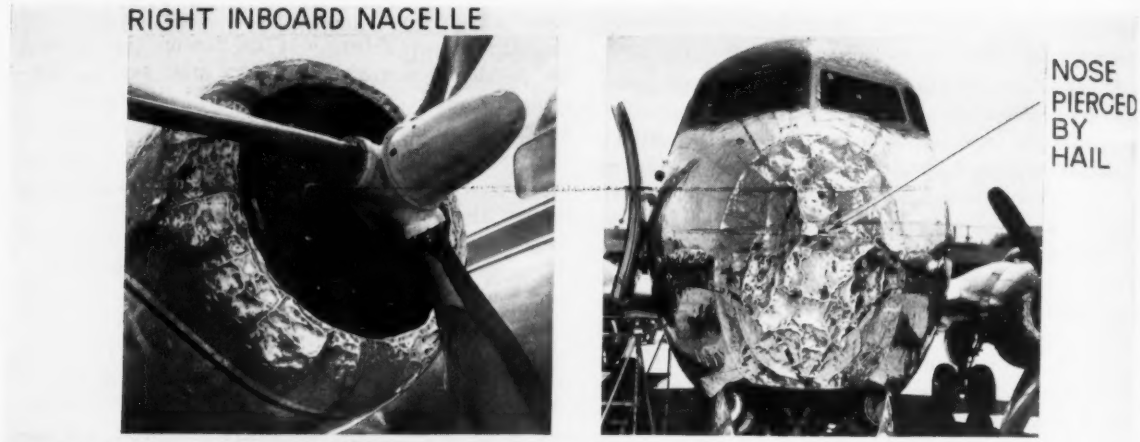

RIGHT INBOARD NACELLE
NOSE PIERCED BY HAIL
NOTE: WINDSHIELDS SHOWN BELOW WERE IN PLACE AT TIME OF HAIL ENCOUNTER.
IN FLIGHT HAIL ENCOUNTER DOUGLAS DC-6
RADIO DIRECTION FINDER LOOPS

FIG. 33.

the British Bristol Britannia with Proteus engines have an encouragingly low sound level. In some installations intake designs give annoying noises where in others they do not. We know that precipitation and suitable ground cover are helpful in promoting attenuation. We are not sure of the reflective or sound directional control possibilities with jet exhaust. We know that some designs of exhaust jet are notably quieter than others. We know that on the ground reflective and absorptive baffles and sound shields can be provided. All in all, I find no cause for pessimism and feel that a wholehearted, intelligent, and vigorous attack on all facets of the problem will bring it to a most gratifying conclusion.

PERFORMANCE DURING APPROACH AND LANDING

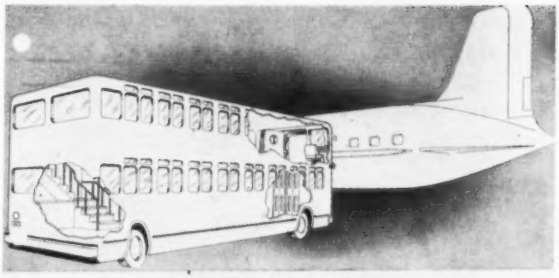
Our somewhat larger, longer range, high-altitude, high-speed transports must be injected into the increasingly crowded traffic patterns at existing airports. Obviously, such aircraft will find their primary use in connection with the larger centers of population, and the runway lengths available do not seem to present any problem with respect to take-off except as to accelerate-stop distance. Power required to achieve the high-speed performances and the relatively low-wing loadings required for efficient operation at the high altitudes would appear to give adequate unaugmented take-off characteristics. There is, of course, some question of variations of take-off performance with temperature, but with reasonable accountability this does not appear serious. On the other hand, we must examine most carefully the aircraft performance during approach and landing. It would be most desirable if all aircraft could have a wide latitude of satisfactory approach and climb-out speeds, such that maximum consistency and good flexibility of operation would be available during the approach and climb régimes to accommodate at any given airport or on any given runway a maximum traffic frequency. If this cannot be accomplished, the situation will, of course, be largely dependent upon the aircraft having the highest required approach speed and the aircraft having the lowest climb speed. Presumably, all other aircraft could, if necessary, speed up their approaches within reason, or

with sacrifices of efficiency decrease their climb speeds, for maximum traffic capacity. Anticipating a fully satisfactory climb performance for our future transport, we must then look to a satisfactorily low approach speed and adequate control to ensure airport efficiency. The existing requirement of approximately 10 per cent residual thrust on approach to provide prompt acceleration, if needed, gives us a difficult problem.

The other portion of this problem is, of course, the landing deceleration. With a clean jet-type airplane without reverse thrust provisions, we are dependent on a super-efficient landing technique and the existence of satisfactory runway characteristics and airplane braking qualities. We can, of course, look to dive brakes and other high drag devices for aerodynamic deceleration during the initial landing run. We might even look to drag chutes for such assistance on emergency fields or in cases of slippery runways or overshoots. However, the effectiveness of such devices rapidly diminishes with loss of speed, and they cannot be considered, in any sense, the equivalent of a reverse thrust producing mechanism for landing safety under all conditions. I look forward confidently to the development of satisfactory reverse-thrust-producing mechanisms for jet aircraft.

Operation of Aircraft

In the field of operation, itself, we must look forward with increasing concern to the possibilities of collision with terrain or with other aircraft, as well as the adverse effects of rain, hail, and turbulence. (See Fig. 33.) We cannot deny that increased speeds make these problems more difficult and the adverse effects more important to avoid. The "see and be seen" principle is already obsolescent in consideration of increasing speeds and air-traffic densities in the vicinity of major terminals. The interim provision of high-intensity flashing lights to help in the air-to-air collision problem is, of course, a worth-while contribution. But, as speeds and traffic densities further increase, such devices do not alleviate the confusion or help solve the problem. It is evident that satisfactory air-borne radar can be beneficial as a defense against terrain collision, can function as a supplementary navigational device, and can help greatly to avoid the high turbulence associated with thunderstorms. As yet, we have no answers except the meteorological approaches to the complete avoidance of hail collision or clear air turbulence; nor can radar be considered a satisfactory device for the prevention of air to air collisions because the rapidity of the relative motions and the confusion of the information presented in this instance. It would seem that the solution to this latter problem lies in the area of more precisely controlled flight paths and patterns with the hoped-for development of cockpit indications and warnings possibly operated on the Doppler principle.



MOBILE GATE HOUSE

FIG. 34.

As to unavoidable turbulence, which may become a serious problem as we cruise faster and modify our descent paths to give high rates of descent for efficiency and perhaps in consideration of the ground noise problem, it is hoped that much more work will be done in the direction of gust-alleviation provisions in basic airplane designs.

Design of Future Transports

We could list innumerable factors of import in the design of our future transports. Some of those affecting ground-handling characteristics are worthy of note. It seems obvious that, if our airplane is to be larger than present aircraft, it will accommodate more passengers; therefore, for safety as well as convenience, careful consideration must be given to the number size, and location of entry-exit doors, as well as to the accommodation of passengers on the ground. (See Fig. 34.) It is amazing that throughout the years air-line passengers have endured the exposure and inconvenience of transition through all kinds of weather between the passenger ramp and the airplane cabin. It now seems that, as our airplanes become larger and more difficult to handle and as our passengers continually increase in total number and group sizes, we should give careful thought to a change from the principle of bringing the airplane to the terminal building, to stationing the airplane at a convenient ground maneuvering and servicing location and conveying the passengers and their baggage and cargo to the airplane by suitable ground vehicles. I well remember that Wm. Delano, of Delano and Aldrich, New York architects than in charge of the architectual designs of La-Guardia Field and later associated with the early studies for Idlewild, proposed the development of a suitable vehicle for handling passengers between a simplified terminal building and the stationed airplanes. The project was abandoned at that time without, I believe, proper consideration of its imaginative promise. Since then, the trends that promoted the thought have become emphasized. The airplanes are larger and will become increasingly so; the passenger loads have greatly increased; the terminal buildings have grown in size and inconvenience; and ramps have increased in length. Required capital investments

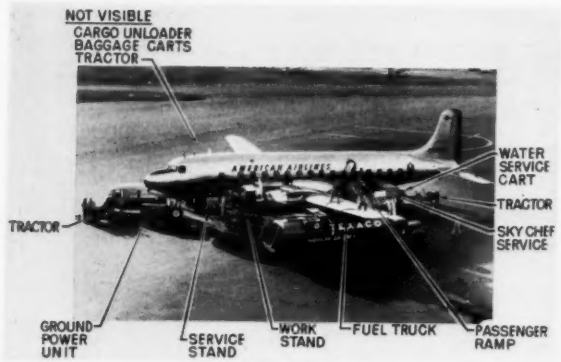


FIG. 35.

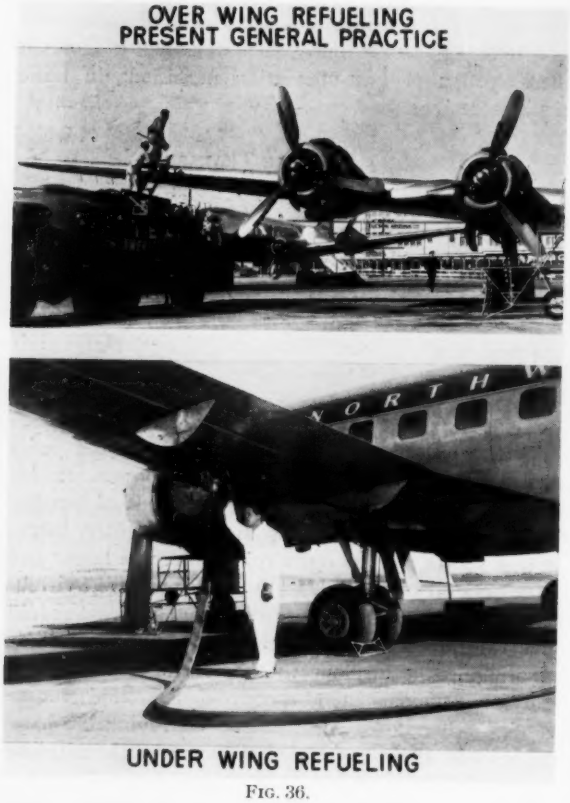
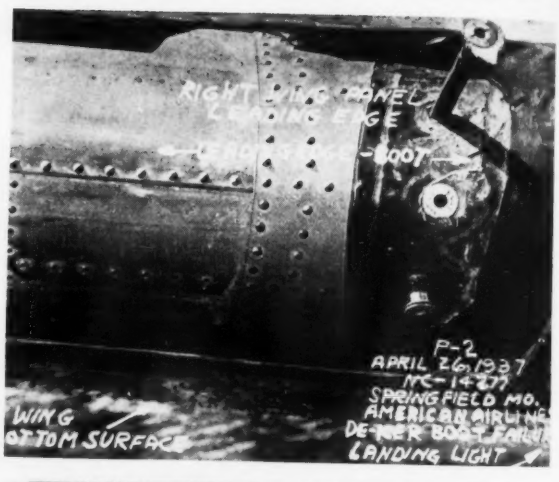


FIG. 36.



DC-3 RIGHT WING DE-ICER BOOT FAILURE

FIG. 37.

and costs have multiplied beyond all reason. One solution now appears to be revival of the earlier suggestion and the development of a proper vehicle to provide weather protection and conveyance from the ramp to within the airplane and vice versa. This entire project was discussed in some detail at a recent S.A.E. meeting by E. W. Fuller, of American Airlines.

We may also hope for design features within our airplane which would greatly simplify the ramp clutter of servicing and cargo-handling equipment. (See unposed Fig. 35.) This problem may well be approached by a consideration of the incorporation in the aircraft of as many self-contained built-in features as is commercially sound, plus the provision of more fixed installations to provide necessary field services, plus a hoped-for combination and simplification of ground units and the services they perform. One obviously desirable and easily accessible improvement would be the provision of under-wing fueling facilities with its increased convenience, economy, and safety. (See Fig. 36.)

FIG. 38.

DESIGNING FOR SAFETY

While we are on the subject of safety, I would like to emphasize some important considerations for the future. First, let us take a look at a lesson we should have learned many years ago and consider how easy it is to overlook the significance of such a lesson. The picture shows a DC-3 inflatable, rubber boot of early design, Fig. 37. The boot, under operating pressure and stretch, started to tear in flight, and the tear progressed unrestrained until the flaying action literally beat the wing skin until large pieces of it tore off in flight as the pilot was seeking an emergency landing place. He barely made it! Immediately thereafter, in consultation with the manufacturers, there were incorporated in boot designs reinforcing strips to stop tears before they had progressed more than a few inches in any direction. (See Fig. 38.) Since then, entirely changed and improved materials for boot construction have accomplished the same tear resistance. Nevertheless, we have failed to design into our pressurized fuselages tear resistance characteristics to prevent an almost exactly similar progressive failure that can multiply the damage of a small penetration to become almost catastrophic. Another picture, Fig. 39, illustrates the point conclusively. The damage shown was the secondary effect of the penetration of a piece of propeller blade, which on leaving the DC-6 fuselage started a tear that under the effects of pressure opened up to remove the top and side skin of the fuselage for an area approximately 10 by 14 ft. The catastrophic possibilities are apparent! Whether or not we will have tear resistance built into our pressurized fuselages is up to the design engineers. The need is evident!

Another factor of aircraft design arrangement, which should need no emphasis but which merits much more consideration than has been given in the past in many designs, is the great safety value of segregated fuel storage locations. Here is a picture of a Convair (Fig. 40), which in pilot training flight was accidentally dropped many feet onto a concrete landing strip. In this airplane, as you know, the fuel is all stored in integral tanks outboard of the engine nacelles—a factor that has shown significant value in a number of instances and in this case clearly shows the extent of damage which can be done to the airplane without affecting the integrity of the fuel storage locations. Many instances could be cited of this and other airplanes where either segregated fuel location or complete severance of wings and nacelles with the same net effect has preserved the fuselage location fire-safe. Suggestions have been made that, in the event additional

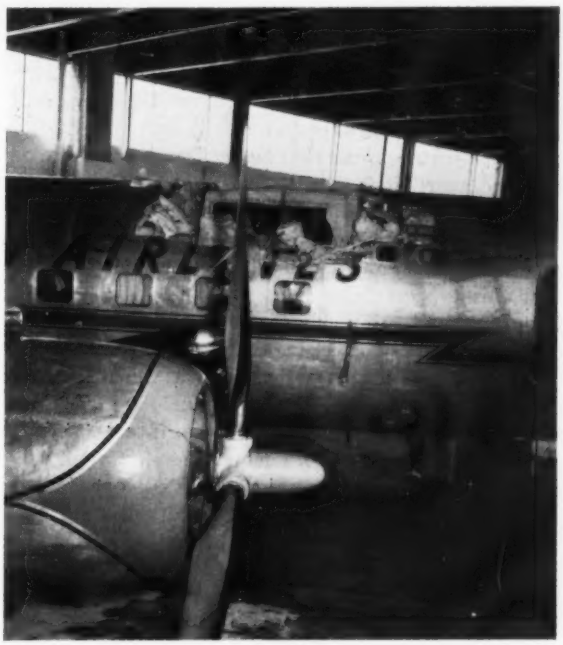


FIG. 39.

FIG. 40.

fuel is required for an airplane and it cannot be accommodated in the outboard wing panels, it can be provided in tip tanks (there may be substantial objections to this) or in thickened cambered sections of the wing (a proposal that may be worthy of careful consideration in the interest of safety). In any event, substantial structure should be provided to segregate effectively all fuel from hazard due to necessary proximity to the fuselage.

This thought leads logically to discussion of a design feature that, to my knowledge, has never been incorporated in any transport aircraft. Over the years, there has been a substantial number of cases of propeller failure resulting in the loss of an engine. The engine usually parts somewhere near its mount units or at the fire-wall, although it has been known to break in various ways. In doing so, it practically always tears loose gasoline and oil connections, and the strains sometimes transmitted by controls reach through the fire-wall and disrupt fuel tanks, emergency valve operations, junction boxes, etc. When one suggests improvement in this type of design, one is usually met with one or two statements. First, that an airplane is not designed to come apart, it is designed to stay together; and, second it is not good design to weaken any particular part of an installation to promote a failure at that point. In answer to the first argument, I would say that this type of failure has occurred with sufficient frequency, and, while we may hope that it will never occur again, it is the equivalent of sticking your head in the sand to say that design thought should not be given to it nor design provision made. In answer to the second argument, I would say that if one conceives a truly sound structure of adequate strength and proceeds to reinforce it in all respects except one, he has automatically created a failure location, obviously without any sacrifice of strength, and has, thereby, done exactly the same thing as designing the structure initially with an intended failure point. Experience indicates that a probable failure point is already indicated; the important thing is to provide the failure details such that, as each occurs, it will be conclusive and definite in its nature and will not aggravate the incidental damages and create the resultant dangers that have prevailed in past failures. This is a principle of design which should be given thought in a number of other installations throughout the airplane. It was given thought, for example, in the instance of the CV-240, where the initial design of main landing-gear fitting attached to the same basic structure as the integral fuel tank such that a gear collapse or failure of the main fitting might well rupture the fuel tank. On examining this detail critically, the design was changed, and the landing gear was entirely divorced from the fuel-tank structure with unquestioned improvement in safety.

We have long been concerned about the cumulative effects of fatigue loading of aircraft structures. Investigations undertaken sometime ago reveal one encouraging characteristic of such failures in usual-type aircraft structures—namely, that development of a fatigue crack is a process that proceeds initially at a slow rate such that the first 20 per cent of the failure may require as much time as the last 80 per cent. The significance of this, of course, is that there is normally plenty of time, particularly in a redundant structure, to determine the existence of incipient fatigue failures. Such, however, is only of value if the structure is capable of ready access for inspection. This is a design "must" that has frequently been neglected. A correlary to this principle is, of course, that the structural elements subjected to fatigue loading should be so designed that in the event of crack development they can be replaced with reasonable readiness. These comments apply to all critical structures in the aircraft and to all major fittings subjected to fatigue loading. It hardly needs to be mentioned that all such structures and fittings should avoid improper stress raising conditions such as notches, holes, sharp cutouts, etc. It has been shocking to find the existence of such design details in critical structures. Experiences in the fatigue field certainly emphasize the value of multiple and redundant structures to protect against the cumulative effects of fatigue.

Another category of design deficiencies which has been too common in transport aircraft concerns the inadequacy of mechanical design details such as bearings, gears, links, cams, and keyed and splined assemblies, which were not adequately designed to withstand reasonable wear without early failure or becoming nonfunctional. As with a chain, a mechanism is only as dependable as its weakest link, and any design detail, the failure of which prevents the system functioning or causes it to malfunction, cannot be tolerated in a critically important system. An airplane is such a complex combination of aerodynamic, structural, mechanical, electrical, hydraulic, and materials engineering, etc., that the overall product frequently suffers from deficiencies in one or another of these categories, and not in fundamental aeronautics.

There have been too many instances in transport design of details that were not fail-safe—upside down bolts that fell out of place in critical locations when a nut accidentally came off; hinges that were located on the wrong side of openable inspection doors or leading edge covers; chair attachment fittings that pulled out of their sockets on minor distortion of the chair structure. We could go on with a much too elaborate list of such deficiencies in design. Wherever possible, assembly units, which for safety must not come apart, should be made with built-in safety locks and a minimum of loose parts that can be omitted in servicing. Good interchangeability should be provided throughout the airplane for all replacable units to simplify maintenance operations and to guarantee satisfactory functioning or replacement. A minimum of simple tools

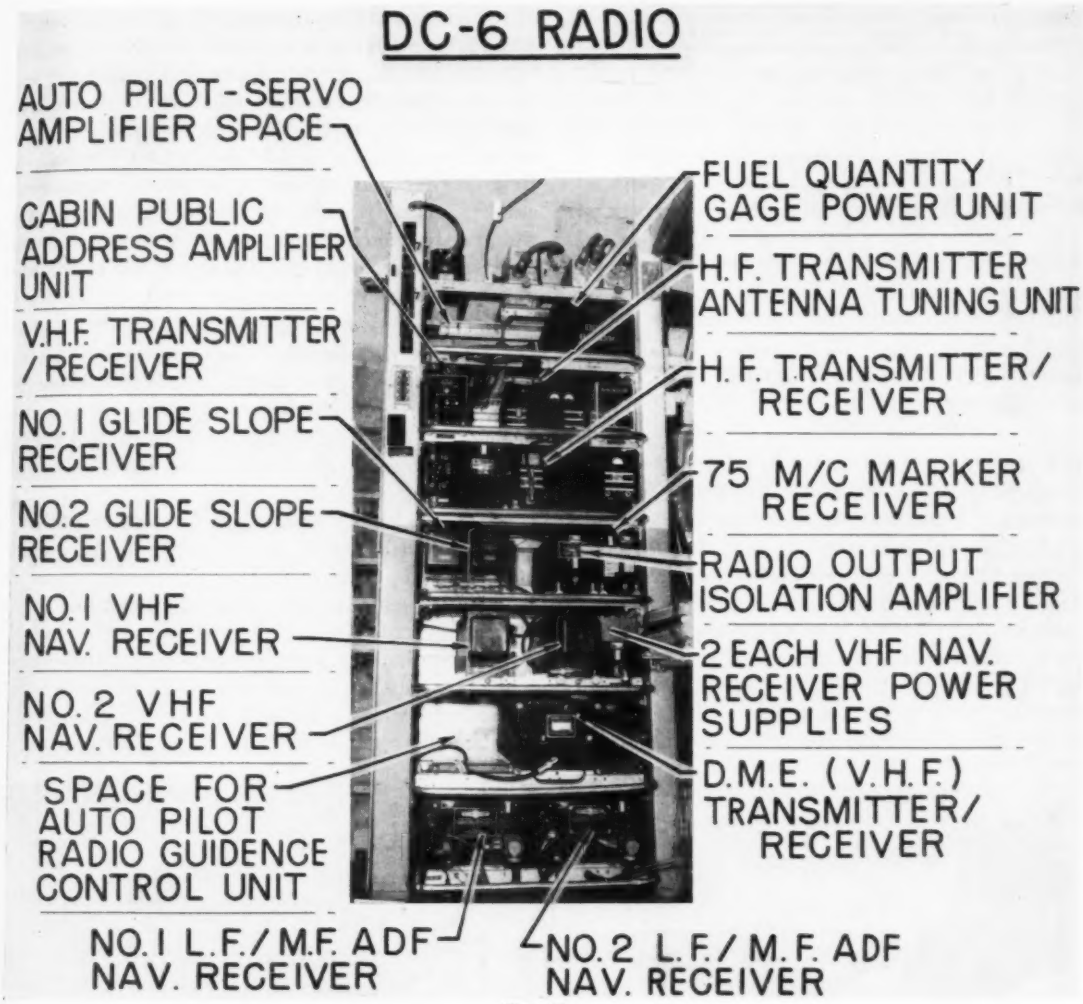

DC-6 RADIO
AUTO PILOT-SERVO AMPLIFIER SPACE
CABIN PUBLIC ADDRESS AMPLIFIER UNIT
V.H.F. TRANSMITTER / RECEIVER
NO. 1 GLIDE SLOPE RECEIVER
NO. 2 GLIDE SLOPE RECEIVER
NO. 1 VHF NAV. RECEIVER
NO. 2 VHF NAV. RECEIVER
SPACE FOR AUTO PILOT RADIO GUIDENCE CONTROL UNIT
NO. 1 L.F./M.F. ADF NAV. RECEIVER
NO. 2 L.F./M.F. ADF NAV. RECEIVER
FUEL QUANTITY GAGE POWER UNIT
H.F. TRANSMITTER ANTENNA TUNING UNIT
H.F. TRANSMITTER/ RECEIVER
75 M/C MARKER RECEIVER
RADIO OUTPUT ISOLATION AMPLIFIER
2 EACH VHF NAV. RECEIVER POWER SUPPLIES
D.M.E. (V.H.F.) TRANSMITTER/ RECEIVER

FIG. 41.

should be required for the performance of all frequently required maintenance operations and replacements. One detail frequently disregarded is the essentiality of easily recognizable safety wire to be used in service to differentiate between those things safetied to prevent accidental use and those safetied to prevent breaking loose. In the one case, you require a high degree of permanence, and in the other you desire only a temporary restraint. The use of too strong safety wire for an emergency operating handle could easily prevent its functioning when required. It has been done!

I would also urge all design engineers, and in fact all aircraft manufacturers, to be on the offensive in the interest of simplification. It is axiomatic that there are many more people who want to add things to airplanes than to take them off. Starting with the President and Board of Directors and proceeding on down through the Sales and Public Relations Department, the Operations Department, the Pilots, Passenger and Cargo Service Divisions, the Maintenance Department, and the air-line Engineering Department itself, there is a continuous development of good ideas, each suggesting the addition of some added complexity, often meritorious but frequently unnecessary and always deserving question. No one apparently is devoted to taking things off. The ultimate effects on weight, economy, and safety are evident.

ELECTRONICS AND FUTURE AIRCRAFT

While we are speaking of existing complexity and the necessity for simplification in our future airplanes, I would like to emphasize the situation with respect to electronics. A DC-6B airplane has among its electronic equipment two H.F. radio transmitter-receivers, one V.H.F. transmitter-receiver, one automatic D.F., one glide slope receiver, one radio altimeter, one autopilot possibly with its black box ILS coupler, one marker beacon receiver, two omni-range receivers, and one intercommunication system. (See Fig. 41.) Other aircraft

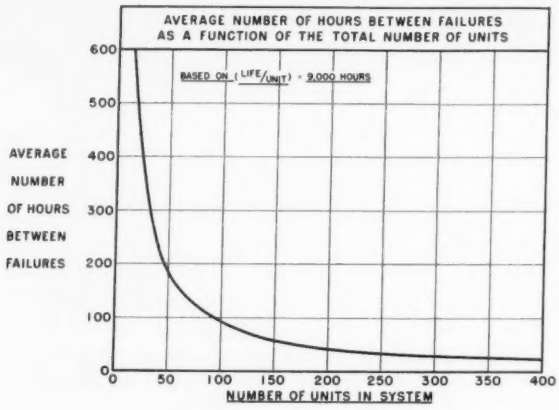


FIG. 42.

of the same type may have, in addition, a Loran receiver, electronic propeller controls for governing and synchronizing, electrical supercharger controls for pressurization superchargers or for engine boost; and, if we look to the future, we will probably have electrically operated fuel regulators, more complex engine-propeller controls, and radar equipment, etc.

A DC-6B as now equipped has at least 350 vacuum tubes. The average life of a vacuum tube in service is estimated to be 5,000 hours. So, you can see the extreme vulnerability to electrical trouble and expense of modern and future transport airplanes. (See Fig. 42.) We do have now in development and available to a limited degree, transistors and associated units that are expected to increase reliability of the electrical devices for which they are suited by many times—currently estimated as 15 times and ultimately 100 times. They will, of course, eventually save weight and space and promote economy. It is hoped they will greatly reduce the cooling problems of high-power electronic equipment, which is one of the main causes of tube unreliability.

The program of miniaturization (Fig. 43) includes development of transistors, capacitors, resistors, and dielectrics by the use of new materials and techniques. It will require a long time to find its way into practical benefits of weight- and space-saving in the aircraft. The units must be developed to be satisfactory functional types, after which they must be applied to commercial electronic units and thereafter installed in the aircraft with significant changes of location and installation. It is impossible to achieve overnight the benefits of such a required chain of events, but we will eventually have them. Miniaturization also involves the application of midget principle to instrumentation and other functional units where size and weight can be reduced without losing efficiency or reliability or can be fully retained with improved clarity of indica-

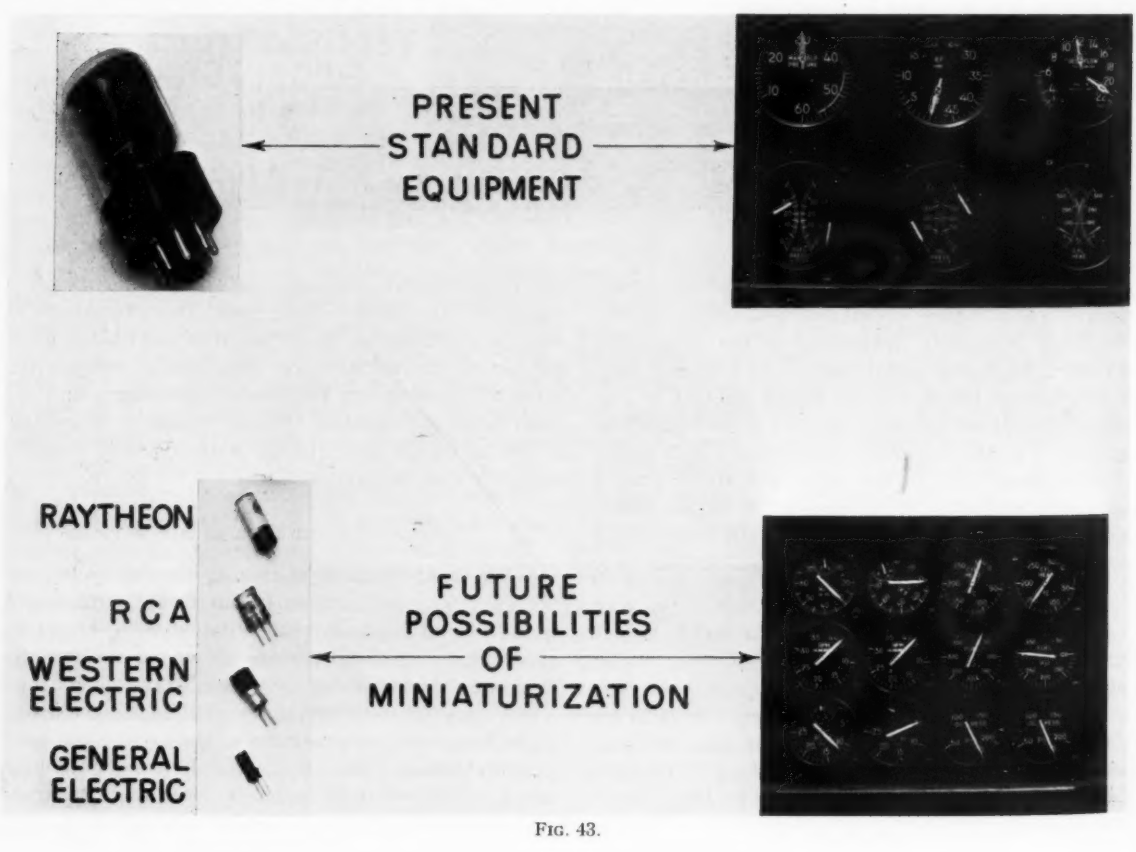


FIG. 43.

tion and maintenance. This whole program is a highly beneficial one headed in the right direction. The significance and importance of the increasing penalties due to the addition of new units of equipment or increase in size complexity of existing units is receiving much attention, as was emphasized by Ed Heinemann's recent discussion of the growth factor in military airplanes. He used a figure of 10 to 1 as the ratio of the total weight penalty applying to equipment weight increases. It is easy to see the significance of some such number, even though we may disagree as to its absolute value, in affecting the efficiency and cost of transport aircraft.

Other Simplifications

Before closing the discussion of simplification, I would like to quote from an address delivered February, 1952, by the Director of Research of the Navy Bureau of Aeronautics. I am leaving out of his quote only those words that refer specifically to the military phase of the problem, but the thought is so applicable to our problem that he might well have written with that in mind. "Are all the gimmicks that we are putting in our aircraft absolutely necessary to insure effectiveness? Or, are we improving ourselves completely out of the picture? I may be pessimistic, but unless this tendency is checked and everyone understands the facts of life, this increased complexity and ever-rising cost will not result in an increased effectiveness overall, but may end up in financial catastrophe." And, if I may quote him out of context, he further says: "If this tendency continues, we will really have the truly safe airplane—it will not fly."

In the past we have tried to develop nice, clean, aerodynamically efficient transport airplanes and have usually ended up by plastering them all over with antenna, radomes, and gadgets until we had paid a significant penalty in performance. Dr. Harald Schutz, of the Glenn L. Martin Company, recently mentioned among future developments in the antenna field (1) all flush-mounted antenna; (2) novel radiation devices such as corrugated surfaces and dielectric slabs; (3) the use, as radiation sources, of apertures such as jet intakes; (4) the use of conductive fluids in plastic canopies; (5) the use of ionized exhaust gases as radiators. Hopefully we will have no external protuberances on our future aircraft except those required for the basic aerodynamic or thrust-producing properties of the vehicle.

Additional Engineering Design Problems

Lest we reach the erroneous conclusion that our air transport engineering job is almost done, or that it is even well along, I would like to mention a few more subjects that are still far from a satisfactory solution and to which I urgently direct your attention. Some of the items deal with the airplane and its equipment and some concern its operation. Some are equally applicable to conventional aircraft of today and tomorrow, and some are peculiar to high-speed jet or turboprop transports of the future. My comments concern safety, efficiency and economy, comfort, and convenience, and there are a few additional remarks concerning the troublesome matter of noise.

It seems obvious that the faster airplanes and higher rates of descent to be employed in the future will allow the pilot less time to trim and adjust his airplane for touch-down. He must start to prepare for his landing further back than is currently the case, and the operation would seem to require a relatively long, straight-in approach. As previously stated, it seems essential that approach performances be given the widest flexibility or be held to values close to those currently used. We must visualize a long period of time during which aircraft of conventional types will comingle with an increasing number of high-speed transports in traffic patterns and airport use. These problems directly affect airport utilization and traffic control techniques, both as to efficiency and safety.

It is also apparent that the work now under way to promote the precision of day and night ceiling and visibility reporting must be carried forward to provide adequate information during that most critical régime of all-weather air-transport operation. We are far from a promise or expectation of full instrument landings and must recognize the exacting requirements of the transition period from instrument approach to final visual contact.

We have mentioned the jet-transport deceleration problem. I would like to stress a few other safety problems associated with the turbo-type power plant. One, of course, is the possibility of mechanical failure, particularly serious with turbine wheels, which, with the tremendous amount of kinetic energy involved, release high destructive forces. This problem can be approached from the material and design angle providing adequate strength, reinforced by cooling, and satisfactory inspection methods, to hopefully ensure against failure. Another approach is to admit that failures may occur from time to time and to protect against their potentially serious results by power-plant arrangement and location or by protective shielding.

Another serious turbo-safety problem is that which involves continued rotation and the existence of extensive internal hot parts in the event of a crash landing. Possible rupture of fuel tanks or lines, even with—or perhaps, particularly with—low volatility fuel, demands adequate fire protection and possibly rapid cooling methods.

We may also have problems associated with the altitude limits of combustion and with relighting in case of jet extinguishment. Mention has been made of the susceptibility of jet-type engines to serious internal damage from intake ice formations and from the ingestion of foreign objects. It is also essential that the

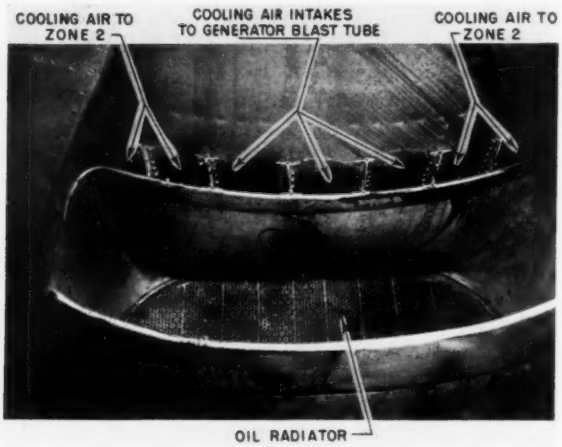


FIG. 44.

acceleration of jet engines in case of required go around on landing be made rapid and dependable. This must be accomplished without invoking surge and without having to retain a too high percentage of rpm and thrust on approach with its aggravation of the landing deceleration problem.

A safety problem associated with noise, or more particularly with the prevalence of structural vibrations associated with jet exhaust, is the increasing frequency of structural failures due to fatigue from that cause. The areas most commonly affected are those directly subjected to the jet flow impulses; however, there has been an increasing indication of other critical failures attributable to high-frequency vibrations originating from the jet characteristics. It is to be hoped that the eventual solutions will decrease or eliminate the noise and structural failures and will promote thrust efficiency.

I cannot adequately emphasize the importance of better cockpit engineering. There are in this consideration elements of safety, convenience, and economy. Active standardization efforts are showing gratifying results, and the entire problem merits your most serious consideration and constructive action. The cockpit must become the center of relaxed, efficient functioning. To this end, it must be adequately roomy and comfortable, well lighted, well heated, well ventilated, and provided with fully adequate vision; it must have a minimum but adequate number of easily operable controls and readily identifiable and readable indications. The cockpit must be an efficient office. It must have a place for everything, and everything must be in its place. A study of the problem will, I am sure, convince you of the tremendous opportunities for improvement.

We must emphasize some rather obvious needs in the improvement of air-transport fire protection. It has been unfortunately true that many power-plant fires have not been detected by the units installed for that purpose. In almost 50 per cent of the cases with which I am familiar, attention was called to the existence of danger by passengers, cabin or cockpit crew, or engine malfunctioning rather than by operation of the fire-warning equipment. This has been due to improper location of detectors, deficient mounting of detectors on materials which failed easily or burned away before detector operation, and sometimes by destruction of detector circuits by fire before the warning was given. There is great need for determination by actual airflow tests of the proper location of detector units and extinguisher outlets under all continuous operating conditions, including the opening and closing of any shutters which may affect airflow in the compartment under consideration. Fig. 44 shows an instance in which shutter operation produced unpredicted airflow conditions adversely affecting fire-extinguisher effectiveness. Fig. 45 indicates how unnoted air leakages establish destructive fire paths with increased damage and nullification of zone fire protection.

The essentiality of preservation of the integrity of systems—particularly those on which we must rely in emergency—seems obvious. Yet all too often one failure induces another—sometimes in an unrelated but essential safety system—and sets up the equivalent of a chain reaction leading to catastrophy. Accident analysis has often shown this. It can be largely prevented by imaginative and thorough engineering.

There is also need for the determination and elimination from all passenger or crew occupied areas or areas susceptible to fumes of the use of materials that produce toxic compounds in the event of fire. It is believed that the explosive-type fire-extinguisher unit patterned after the tank explosion suppression devices developed in England might produce an effective and lightweight engine compartment-type extinguisher to cope with the unfavorable airflow conditions existing. Investigation and development of such applications is urged.

One of the currently popular subjects for discussion in the safety field is whether or not seats should be faced forward, backward, or sideways. Hugh De Haven has, I believe, cryptically stated the uncertainties of the problem when he asks the question: "What types of rearward-facing seats are how much safer than what types of forward-facing seats?" It is obvious that turning our existing seats to the rear would provide no more, if as much, safety than at present. We have not yet analyzed exactly what it takes to determine the relative safety of the several seat directions. Dynamic load studies are required. We have previously suggested that the approach to the problem of accident survival should be based on the known loads which the human body, properly supported, can tolerate. This thinking carried along in the design of seats to face in any direction, can I believe, develop equivalent safety in all directions and eliminate this rather futile debate from our list. I would suggest that any action or regulation that limits the direction of

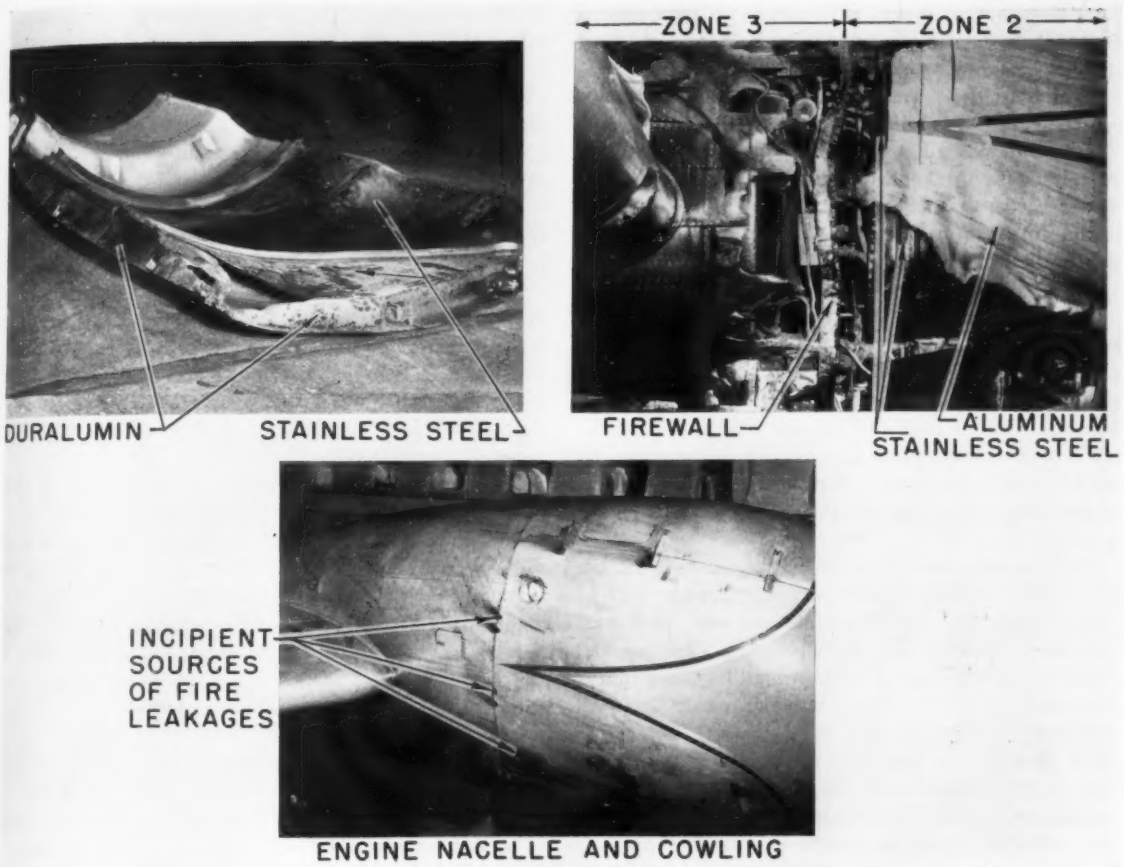


FIG. 45.

seat facing in transport aircraft would be premature and ill advised.

We still have instances of freezing of controls or of difficult operation due to inadequacies in design with respect to the effects of low temperature. Inadequate clearances in such systems in the presence of small amounts of moisture can result in locking from freezing. Unnoted leakages of liquids onto control elements can, when combined with low temperatures, cause the same effect. Differential expansion of materials can cause trouble when combined with inadequate running clearances. These are engineering problems.

PROBLEMS OF THE FUTURE

I would like to mention the importance of designing into our land-planes to be operated over water much more adequate and specific provisions for flotation and ditching than have prevailed in the past. Reliance on empty fuel tanks is, in my opinion, insufficient, as is the assumption that the hull, wing, or tank structures may not be substantially damaged in a ditching.

There are a whole series of jet power-plant problems yet to be resolved in the area concerned primarily with efficiency and economy. One is the extremely adverse effects of high temperature on jet output. The question involved is, of course, one of temperature accountability. It would appear that the objective to be sought would be the achievement of a principle of temperature accountability that would produce the same adequacy of reserve performance encompassed in the present 50 per cent temperature accountability with reciprocating engines. Full temperature accountability would, of course, maintain under all temperature conditions the full reserves for ideal conditions stated in the Civil Air Regulations, including the normal 50-ft. obstacle clearance. At the other end of the list, no temperature accountability would normally result in the loss of the entire 50-ft. margin at a temperature of approximately 85°F. Fifty per cent accountability retains a percentage of the total margin all the way to 120°F. This is believed to be a satisfactory and sensible compromise, and its retention in principle is recommended for future jet operations.

Another important jet efficiency problem is that associated with specific fuel consumptions. It appears now that we can hope, at some time in the future, for fuel consumptions per hour per pound of sea level thrust approximately twice those to be anticipated per equiv-

alent horsepower hour with improved turboprop power plants or with the latest reciprocating compound engines. We are far from achieving such jet consumption values at the present time. These figures are not directly comparable but are indicative of a most serious jet range and economy problem. Consumption rates are related to intake losses and ram recovery, compressor ratios and efficiencies, combustion efficiency, turbine intake temperature and efficiency, mechanical efficiencies, and jet outlet efficiency, configuration, and manipulation. Some of these factors are inherent in the power plant itself, and some are functions of the power-plant installation and operation. We may well be faced with the same problems as in the past in reconciling the installed results with those determined in test-stand operation!

We also look forward hopefully to substantial reduction in indicated power-plant first costs and to great improvements in engine overhaul periods and attendant costs.

There are also efficiency problems associated with the introduction of high-speed transports into the current airport air-traffic and ground-handling problems. Much work must be done in those areas. The jet does not have the flexibility of air or ground handling that is now available with conventional aircraft or that will be common to the turboprop type.

We must also examine closely the significance and value of the so-called derating of jet power plants—that is, the determination of proper commercial transport operating ratings as compared with the approved military figures. It is obvious that engine reliability increases as an inverse function of turbine intake temperature and speed and with some benefit in specific fuel consumptions. However, such derating is inevitably accompanied by decreased thrust available and increased specific power-plant weights. The degree of compromise necessary and desirable is yet to be determined and is to some degree a function of the state of the art.

We must also determine and evaluate the effects of nozzle shape and adjustment and techniques of power plant operation affecting cruising efficiency. We are faced with a serious problem in the relatively high fuel consumptions for taxiing operations. And, here we meet some airport problems. Consideration must be given to possible damage to runways and run-up areas due to blast, heat, and fuel spillage. These effects are influenced by the character and materials of pavement construction and by the proximity and direction of the jet exhausts relative to the ground. Augmented take-offs would greatly aggravate these problems. Taxi strips and holding areas must be designed to permit high taxiing speeds to conserve fuel and to minimize taxiing distances. Aprons and airplane loading areas must give protection against blast and heat to structures, equipment, and personnel and must adequately control objectionable noise. We have mentioned the possible desirability of the so-called "Movable Gate House" principle. We may wish to handle large airplanes, particularly jet types, that way, while continuing to handle the smaller transports at conventional ramps, in consideration of the convenience of so doing and the importance of small time-savings in the shorter ranges of operation.

We must closely examine the nature and costs of fuels to be used in commercial operations. Current jet fuel specifications are based largely on maximum availability with satisfactory characteristics, which may or may not produce the same answer as a satisfactory fuel of minimum cost. Turbo engines can be developed to operate satisfactorily and efficiently on a wide variety of fuels. Fuel costs are such a large percentage of jet operations that this economic factor must not be neglected.

An important consideration in realistic economic studies is the adequacy of assumptions of operational fuel reserves. A tentative suggestion that has been discussed with some of the aircraft and power-plant manufacturers is to assume a 45-min. weather hold at 20,000 ft. at destination, followed by a descent to attempted landing, then a climb-out to 20,000 ft. and a cruise to alternate of 300 miles, followed by an additional hold of 45 min. and descent to landing. This would appear to be a fairly drastic reserve requirement but is not incompatible with operational requirements under extremely adverse weather conditions. It appears that, with axial-flow engines of modern design, there is relatively little difference in the fuel consumption ratios of four- and two-engine holding, and—quite differently from Comet-Ghost experience—no particular penalty is paid.

It is to be hoped that research may disclose satisfactory methods for determining the existence of internal jet power-plant conditions that are signs of progressive deterioration. With the manifold opportunities for internal troubles in multistage axial compressors and tubines and in view of the tremendous expense involved in unnecessary removals and overhauls, it would be of immense benefit to jet economics if methods can be determined for detecting and forestalling serious mechanical troubles, serving also perhaps as a most logical basis for overhaul.

Much additional information must be obtained to establish the most efficient jet operating altitudes. It seems a reasonable conclusion based on recognizable limitations and relations of wing loadings, speeds, and power-plant characteristics that the probable altitude range of efficient jet-transport operations will lie between 30,000 and 55,000 ft. Once the 30,000-ft. operating altitude is exceeded—and exceed it we must for jet operations—the problems are largely ones of degree and not of nature. We must have absolute assurance of no decompression failures. Until recently, much thought was given to anticipated commercial jet operations to approximately 40,000 ft.,

DE HAVILLAND "COMET" 4 GHOST
TURBO JETS GROSS WEIGHT 105,000 LBS.
A. V. ROE "JETLINER" 4 ROLLS ROYCE
DERWENT 5 TURBO JETS GROSS WEIGHT 65,000 LBS.
VICKERS "VISCOUNT" 4 ROLLS ROYCE
DART TURBO PROPS GROSS WEIGHT 59,000 LBS.
BRISTOL "BRITANNIA" 4 BRISTOL PROTEUS III
TURBO PROPS GROSS WEIGHT 150,000 LBS.

FIG. 46.

but more recent information has indicated that this may be a somewhat undesirable altitude, at the approximate base of the tropopause, with prevalent turbulence and high wind conditions. It would appear, therefore, that jet-transport operations may often be conducted at altitudes somewhat in excess of this and that for the retention of a reasonable bracket of efficiency factors they should not frequently be too much lower, although 30,000 ft. may often prove necessary and desirable. It has also become increasingly apparent that at the higher altitudes jet stream velocities must be reckoned with and avoided if they are in an unfavorable direction, and that the boundaries of such jet streams must be traversed in the shortest time to minimize the undesirable turbulence.

SUMMARY

We have tried to show that from the diversified air-transport equipment of 25 years ago, there emerged a simple and consistent type generally common to the air transportation activities of this country and of the world and varying principally in sizes, capacities, arrangements, and performances. We are now at, or by British standards, just over the threshold of a revolutionary change in air-transport propulsion. There are some significant changes indicated in the airplanes themselves, involving refinements of aerodynamic cleanness and form, and substantial extensions in speed, altitude, and associated performances, equipments, and requirements. For many applications of the indefinite future—notably the local or short-range operating field—drastic changes in existing characteristics do not appear to be necessary or desirable. There will, in any event, be a protracted transition period during which the substantial changeover will be effected. We must never forget that effective speed is of the essence of air travel, and in spite of possible economic problems and technical difficulties, the availability of that speed with adequate safety, dependability, and comfort will find extensive use in the essential advances of this country and of the world.

It must be frankly admitted that as of today our friends across the sea—the British—have a substantial lead on us in the accomplishment of a limited area of high-speed transportation. (See Fig. 46.) This, I believe, is due largely to the existence of an adopted and implemented program of British aviation expansion, both military and civil. In 1918, Lord Northcliffe, then Chairman of the British Civil Air Transport Committee, stated: "Cost what it may, this country must lead the world in civil aerial transport." For a number of years, the British led down that path. However,

CONSOLIDATED-VULTEE CV-240 WITH
2 ALLISON T-38 TURBO PROPS

FIG. 47.

starting in 1927, and for 20 years thereafter, American enterprise acquired and retained the leadership in both quantity and quality of air transport. The reaffirmed and implemented British policy of the days immediately following the second World War certainly threatens to transfer that leadership in quality of performance, if not in quantity. With the technical facilities for research and development and the knowledge and capacity at our command, we could easily re-establish our preeminence in air transportation. However, I am bold to state that, before it is accomplished, there must be some evidence of reassertion of the pioneering spirit that has always characterized American industry and which has now apparently deserted the plans and activities of the American air-transport operating and manufacturing groups. Fig. 47 shows our only flying entry now in the turbo-transport field!

We do not want in America the Government domination of the air transport manufacturing or operating industries which prevails in Great Britain, but we do want some semblance of the results that have been obtained thereby. There must, I believe, be a basic change in the attitude of our aircraft manufacturing industry toward the desirability and practicability of producing high-speed transports. I do not hesitate to include in this the power-plant manufacturers and the unannounced group of accessory and equipment producers, whose products are essential to the venture. Lacking a controlling national program in this field—and we would not wish to have any such—we must rely on the courageous leadership of private enterprise to stimulate action. I would say that there is little likelihood of selling high-speed transports in the design and development of which prospective customers have had no voice. We have seen today that the graveyard is replete with such projects! Nor, is there much likelihood of selling units, either power plant or air frame, which threaten to cost anything like the numbers that have been recently quoted in the American press. The figures just do not smack of reality, nor of any real desire to do the job, nor do they indicate any willingness to take a reasonable American industrial risk in the doing of it. I would hate to think where we would be today if that spirit had characterized the 25 years of air transport just passed. It is my fear that unless there is a substantial change in our attitudes and accomplishments, the manufacture of high-speed air transports will depart from these American shores just as did the Merchant Marine of the past. It *can* happen again!

My final exhortation, then, is to reappraise the situation honestly and evaluate the risks we can afford to take and the risks we cannot afford *not* to take. We of the air-transport industry admit our concurrent responsibility and would be happy to join with the designers and manufacturers in bringing about the early availability of the world's best high-performance transport airplanes.

Discussions of the Lecture

W. T. Dickinson, Executive Engineer, Douglas Aircraft Company, Inc.: It has been most interesting and instructive to hear Mr. Littlewood's lecture on the history of commercial aviation and his prognostications of the problems and trends of the future. As a matter of fact, it has always been one of my pleasantest experiences to engage in debate with Mr. Littlewood on any phase of the aircraft manufacturer's or air-line operator's business. As you might suspect, there is a wealth of material in this lecture which will supply the basis for many happy arguments in the days to come. I would like to select just a few.

Mr. Littlewood says that a modern aircraft specification should include the advance determination of, and a plan for, capacity growth. Indeed it is true that airplanes of the past have grown during their lifetime. It also sounds logical to plan for the future. However, "planning for future growth" usually means making things a little larger than they need be. Perhaps this fitting should be a little stronger because the next model will weigh 10 per cent more, or that cutout ought to be somewhat larger because the next size wheels, engines, superchargers, struts, fuel tanks, or what have you, must be provided for in the next larger version. The point I would like to make is that, if "planning for the future" means increased weight and drag, the *original* model may never even live to grow up.

I would like now to touch lightly on the subject of simplification of aircraft. This is a fine modern subject for discussion. As Mr. Littlewood has so aptly put it—everyone from the President on down wants to add things. This also rightly includes Vice-Presidents, too,

for I note that the following significant additions have been suggested here tonight:

(1) Terrain, aircraft, rain, hail, and turbulence collision avoidance devices.
(2) Gust alleviator provisions.
(3) Jet reverse thrust producing mechanisms.
(4) Underwing refueling provisions.
(5) Pressurized fuselage tear resistance.
(6) Additional flotation and ditching gear.
(7) Built-in ground servicing features.

I have made some inquiries but I have yet to discover any equipment or article that was formerly carried on transport aircraft which is not still required, unless you wish to count the pilots' raincoats, which were standard gear in the DC-3 and are no longer required in pressurized aircraft.

Aircraft are certainly becoming more complex every day, and the reason is that the operators find it necessary in the competitive scheme of things to demand that airplanes do more and more things. For example, in that 15 years the speed range has increased from 70–260 to 100–600 m.p.h. and the altitude range from sea level–15,000 ft. to sea level–50,000 ft., refrigeration systems are now required, and each year the airplane must cope more satisfactorily with every kind of weather. All of which brings us to the subject of cost. Mr. Littlewood seems to feel that the new transport costs he has heard are unrealistic and undemocratic. I do not profess to know what a new jet transport should cost, but I do know that, for the above reasons and many others, they will most certainly cost more than the current *bargain* rate of $20 per lb. of weight-empty for today's piston-engined models. How much above $20 per lb. the figure will go will be strongly affected by how many airplanes a manufacturer thinks he can sell. With five major transport manufacturers gnawing at the market, who can say what the future holds.

In any event, as a prospective customer, Mr. Littlewood need not worry about his voice in future Douglas Company transport designs. This fine lecture and our past associations indicate clearly that his vocal chords need no oiling, and his comments have always been held in high esteem.

Frank W. Fink, Chief Engineer, San Diego Division, Consolidated Vultee Aircraft Corporation: I would like to congratulate Mr. Littlewood on an excellent paper presenting a brief history on air transportation over the last 25 years and portraying the technical trends and some of the technical problems of the future.

I believe the three most important subjects discussed in Mr. Littlewood's paper were simplification, standardization, and safety.

Simplification is a must if we are going to continue to build aircraft for our air lines which are economically feasible both to manufacture and operate. Mr. Littlewood mentioned several developments on the horizon which would aid simplification, such as transistors and miniaturization; however, I would like to emphasize that there are many items that do not require research to accomplish. I am thinking of such things as a common power supply for all the electronic equipment in lieu of a separate power supply on each piece of equipment; the use of three gyros with repeaters, rather than some six or eight gyros in each airplane, and pneumatic systems with single supply lines in lieu of hydraulic systems with supply and return lines.

Standardization is also an excellent way to reduce costs. I would like to ask the question: "Why is it that two air lines operating the same type aircraft, over the same routes, under the same regulations, and even with an interchange agreement, cannot standardize on the same radio equipment?" Standardization does not mean, or should not mean, that it is necessary to use obsolete equipment, but if the air lines would agree to standardize when new modernized equipment is available their costs would be greatly reduced.

As for safety, too much can never be said on this subject, and Mr. Littlewood does an excellent job of discussing it. I would like to state, however, that the industry as a whole should spend more time and effort on preventing crashes rather than on trying to prevent casualties in the event of a crash.

Two or three other points I would like to comment on. Mr. Littlewood mentions the probable range of jet transports would be from 500 to 2,500 miles with turboprops below and above this range. I feel sure that, once we have a good turboprop engine available, it may prove to be so much more economical and versatile than the straight jet on the complicated domestic route system with small airports, alternate fields, temperature extremes, etc., and that it will fit into the entire range picture. And as for helicopters, I agree that they must be simplified and have two-engined reliability, but they should not be overlooked for ranges up to 200 or 300 miles, since a higher passenger-mile rate can be charged and still have a trip cost less than present airplane plus limousine or taxi trip cost.

The subject that was conspicuous by its absence in Mr. Littlewood's paper was air cargo. Since this field will undoubtedly expand to far greater volume than the air passenger business, some of the technical trends in this field would have been interesting.

One final comment, Mr. Littlewood mentions that landplanes to be operated over water should have more adequate and specific provisions for ditching. Any treatise on future trends should not overlook the probability of seaplanes returning to the overwater transport routes.

I would like to compliment Otto E. Kirchner on a fine presentation of Mr. Littlewood's excellent paper.

Charles Froesch, Vice-President—Engineering, Eastern Air Lines, Inc.: I want, first of all, to highly compliment Mr. Littlewood for his clear, concise, and forceful presentation of the technical trends in air transport.

The all-inclusiveness of the subject defies its coverage in a single paper, since the many phases of air transportation require a good size book for their proper discussion, but in this 16th Wright Brothers Lecture, Mr. Littlewood has, in his inimitable and masterful way, presented thoroughly and logically the most important problems facing the aircraft designer and the air-line engineer today.

He has done so, frankly, basing many of his opinions and recommendations on past experience, a keen assessment of the present, and common sense.

I am delighted to say that I am—almost—in complete agreement with all the thoughts expressed in his dissertation.

As I read his chronological description of the historical background of air transport, starting back in 1927, I could not help but speculate as to what would have happened if the General Aviation GA-43 trimotor had been completed and flight-tested before the Douglas twin-engined DC-1. The air lines, instead of disposing of their DC-3's today, would probably be selling their GA-43 trimotors!

Mr. Littlewood observes that there has been a tendency to increase the size of essentially short-haul transport aircraft in the past, as witnessed by the 12- to 15-passenger capacity of the Fords, Fokkers, Condors, and DC-2's of the early thirties, to the 36- to 44-passenger capacity of the Martins and Convairs today.

History has a way of repeating itself, since this range in seating capacity parallels that of the bus industry in the twenties when 15- to 20-passenger jitney buses were prevalent in scheduled bus operation. Today most motor buses have a seating capacity ranging from 40 to 50, except for special applications.

Seating capacity is dictated by the type of service to be rendered and the traffic requirements.

Local schedule aircraft operation is similar to suburban bus transportation. It is, therefore, not a coincidence that the seating capacities of these two forms of transportation are similar.

Mr. Littlewood implies that a 50 per cent average load factor is the highest we ought to maintain to achieve maximum public service and utility. This appears to be on the low side, since the experience of other long established means of transportation clearly indicate that an average of 55 to 60 per cent permits the rendition of good public service and is economically sound. To go higher, of course, results in providing inadequate public facilities.

With regard to runway length requirements as projected up to 1960 and beyond and illustrated by Fig. 24, it is hoped that the permissible tolerance will not continue to spread as shown by the shaded areas.

Certainly, it should be possible to maintain a maximum of 6,000-ft. runway length for any domestic operation and not more than 8,000 ft. for a long-range aircraft, bearing in mind that the cost of airport real estate becomes prohibitive as airport size increases.

Practical limitations of runway length is also an effective means to impress the aircraft designer on the necessity of retaining approach and landing speeds at reasonable values.

While it is perfectly true that navigational aids have greatly improved and are becoming more dependable, we must not forget that in the final analysis, pilot judgment—the human element—dictates the landing characteristics and performance of transport aircraft. Human reflexes can be trained but they cannot be changed.

Pilot reaction time is the fundamental factor that must receive the most serious consideration when engineering transport aircraft cockpits. The high subsonic speeds contemplated with jet transports require the highest degree of functionalism in cockpit arrangement. Much more thought must be expended on that part of the aircraft than heretofore.

I also want to emphasize Mr. Littlewood's observation on the tendency of the design engineer to minimize the importance of operational fuel reserve requirements—that is, the differential between zero fuel and landing weights. This has on many occasions severely penalized pay load in inclement weather operation.

It is on the question of wing location that I find myself unable to agree fully with Mr. Littlewood's conclusions.

There is no doubt that, essentially, the low-wing all-metal airplane has real advantages from an economic point of view, as well as crash safety, and I fully subscribe to this design philosophy for high-speed passenger aircraft, although a mid-wing arrangement with a so-called "double bubble" fuselage, to provide adequate baggage and cargo capacity below floor, may be just as satisfactory.

However, a high-wing location offers a decided advantage for cargo-carrying aircraft where cargo-loading floor height must basically be that of truck platform height to eliminate lifting and lowering operations in cargo handling.

I am ever mindful of American Railway Express' motto, which states: "When you drop it, you buy it." We have "bought" too many shipments in the past.

Cargo-operating experience clearly indicates that for medium hauls—in the order of 500 to 1,000 miles—the cost of cargo handling is excessive, if not prohibitive, to justify this type of operation economically, and competitively, with low-wing aircraft, which have a loading platform 8 to 10 ft. from the ground.

What we must strive for is virtually a flying box car and, again, drawing from surface transportation experience which is highly competitive costwise, it may well be that the cargo container should be quickly removable

to permit highest possible utilization of that part of the aircraft which is most expensive—that is, the power plant and lifting surfaces.

I feel that this problem has not been fully explored and deserves more consideration before we can economically sustain a large-scale cargo operation domestically.

I, too, wish to enter a plea for the standardization of many aircraft parts and components that are common to all, particularly safety items such as doors, locks, and emergency exits. The same passengers fly on all air lines. Why should the windows, the lighting fixtures and controls, and lavatory accessories be different? This is an area where immense savings can be effected by suitable cooperation between the aircraft manufacturers and the air-line industry.

Another transport aircraft problem that requires serious consideration and a far more practical solution than heretofore achieved is baggage stowage provisions, particularly with regard to accessibility. Passenger baggage handling today is too time-consuming. It is provocative to the air-line passenger and expensive to the air-line operator.

It doesn't make sense to transport our passengers at 500 m.p.h. if we let them wait at their destination for possibly up to 25 per cent of their flight time to deliver their baggage.

This operation often involves rehandling the baggage several times from the moment the passenger deposits it on the weighing scale at the ticket counter and claims it at the end of his trip.

Furthermore, ways and means must be found eventually to eliminate the millions of baggage tags used yearly and, perhaps, adopt handling procedures similar to those of surface transportation carriers.

I do not share Mr. Littlewood's pessimism about helicopters for local schedule operation. Certainly the solution of the technical problems involved today before we can consider helicopter transport operation a daily routine is not dissimilar and magnitude to that applicable to jet engines insofar as reduction in fuel consumption and attainment of absolute freedom from turbine wheel burst are concerned.

Furthermore, the substantial improvements in highway facilities to reduce traffic congestion and promote the more efficient use of the motor bus and the automobile will have a profound effect on short-haul air traffic.

There is only one of two things that I can see which can be accomplished to combat this perfectly normal rate of progress. Either we discontinue local schedule operation with our present type of equipment or use helicopter transports operating from heliports located much closer to traffic generating centers than airports can ever be.

The utility of the helicopter, or, perhaps, some form of convertiplane, offers overall speed and convenience that the traveling public will require us fully to exploit.

Even today, the overall cost of transportation per mile from point of traffic origin to destination indicates only a narrow margin between ground and air transportation combined and the helicopter, in spite of the latter's now inefficient configuration.

The problem of noise abatement is, indeed, a serious challenge to the aircraft industry. It is a perfectly normal reaction to associate noise with danger when thinking of aircraft. Yet, heavy truck traffic, which creates approximately the same noise level and is far more dangerous to both surface vehicles and pedestrians alike, as can be attested by the fatalities that occur yearly, is tolerated as a matter of fact.

We accept the odd 40,000 deaths yearly due to motor vehicle accidents rather casually. We pay little attention to the millions of human beings hospitalized yearly by motor accidents, but when a fatal aircraft accident occurs, we think of the aircraft as a death-dealing device. Why?

Perhaps the average person has not yet fully accepted man's successful effort to overcome gravitation in spite of the many advantages offered by air travel and its necessity in today's industrial tempo.

Perhaps it is because the frequency of propeller and engine exhaust noise of aircraft is intermittent and often occurs during the hours of the day when the surface traffic noise level is at its lowest, thus accentuating the noise created by air traffic.

Perhaps it is because the noise instills a fear of danger and has a disturbing influence. On the other hand, millions have accepted the high noise level of the elevated railways in some of our large cities and think nothing of it.

Be that as it may, it would seem that, if we can attenuate noise, we will satisfy most people regardless of safety, strange as this may seem.

Excellent examples in the past have been the automobile, the motor truck, and the motor bus. Many of you will recall the snorting of motor bus exhaust and the poor mufflers and cutouts with which automobiles were equipped in the early days.

Improvements were made and everyone was satisfied but has motor vehicle safety been increased? I will let you be the judge. Yet, do we close streets or highways after a series of accidents? Of course not. We try to do something about it.

Fortunately, the attenuation of aircraft noise offers many avenues of research yet unexplored.

It is believed that once we reach an understanding of noise generation and propagation, ways and means to control it will be found. It is a problem that will tax our knowledge and analytical ability.

I have read with interest Mr. Littlewood's comments on detail design as affecting servicing and maintenance of aircraft and fully concur with his recommendations. This is a fertile field for the designer who often overlooks serviceability in favor of low weight and best possible performance. Simplification and the elimination of

unnecessary gadgets has also a direct bearing on maintenance costs, since any unnecessary device does not only involve original cost, weight, and maintenance during its life but also shop space, equipment, and stowage space.

An air line is an agency created to serve the public safely, speedily, and comfortably. To do so, the airline engineer must remain a perfectionist, assess past experience, and review with a critical eye what is proposed for the future.

Mr. Littlewood has, indeed, very ably done so.

Colonel Francis C. Gideon, U.S.A.F., Director of Operations, Military Air Transport Service: I appreciate the invitation to participate in these Institute proceedings. The command that I represent, M.A.T.S., feels itself very much allied, because of its mission, with civil aviation, and we welcome any opportunity to share our views with the aviation industry in forums of this nature. I should like in the interest of adding zest to this discussion to take serious issue with Mr. Littlewood. However, I find that most of the positions he has taken in his fine presentation are unassailable. There is one difference of view which I should like to bring out. Generally speaking, however, I can only emphasize certain points he has made and stress agreement with them.

The one point of major difference in our views is that we do not write off the potential of the high-wing airplane for the military air transport mission. We believe that the inherent advantages, due to the fact that the high wing permits a truck bed height loading operation, are sufficient to warrant serious consideration of the high wing design. This comment is not necessarily in conflict with Mr. Littlewood's presentation in that I am sure his comments are confined almost entirely to passenger transports, whereas my views would stress the cargo-carrying operation. The significance of an aircraft configuration that facilitates the handling of cargo becomes greater as we look forward to the time when we shall be engaged in a true "air freight" operation, handling large volumes of all kinds of cargo, as distinguished from the present "air express" operation, which describes both the military and civil cargo operation today.

I should like to emphasize the responsibility of aircraft engineers, as well as operators, for incorporating and utilizing the best possible designs and procedures for passenger safety. Such things as proper location of all emergency equipment to provide maximum safety, proper briefing of passengers in the use of equipment, and skilled flight attendants are necessary to ensure that in event of emergency the most effective actions are taken.

A more serious problem that we hope the engineers will solve without further delay has to do with the icing of wings and control surfaces. Icing is still a mysterious business, and every new airplane seems to offer a new challenge to the engineer and operators. Our weather forecasting has improved and we are able, in many cases, to avoid serious icing difficulties, but forecasting is not perfect and taking it as it is, our transport airplanes must be designed to cope with a lot of ice and operate safely.

A great deal of emphasis should be given by all agencies interested in air transportation in improving the design of air fields, passenger- and cargohandling facilities at terminals, and materiels handling in general. The hydrant refueling technique eliminates to a certain extent the confusion in the servicing area and its use should be encouraged. Development of suitable container or alternate packaging for fast handling and fast distribution of cargo should be investigated to the end that better handling facilities are developed without undue tare weight penalties. Terminals should be designed and constructed for rapid passenger and cargo movement with the least possible handling.

We can anticipate aircraft designs that will give us higher flying, faster, and more comfortable transport. We look forward with confidence to the advent of the jet transport. This transport lends itself ideally to the air movement of our most precious cargo—people. This very trend toward the jet transport suggests a departure from the theory of an all-purpose transport. The advance of engineering, it would appear, will compel us to adopt the jet transport for our personnel operation and to take maximum advantage of the lower performance, high-capacity freight airplane for handling of large volumes of cargo.

Of all the points that Mr. Littlewood's lecture has raised and which should be emphasized, the foremost, I believe, would be his plea for simplicity. The greatest contribution of engineering skill would be toward simplification in the cockpit, in the air frame, and in the power plants of our transport airplanes. We in the military are plagued with a high rate of turnover of our personnel and the complexity of our modern airplanes magnify the normal problems of rapid attrition. We will be satisfied, I suppose, only when the engineer develops an air frame with no irregular surfaces and power plants with no moving parts.

Charles F. Horne, Administrator of Civil Aeronautics, C.A.A., Department of Commerce: I appreciate the opportunity of discussing Mr. Littlewood's impressive paper on the "Technical Trends in Air Transport." The paper contains a wealth of information brought into focus and perspective by virtue of Mr. Littlewood's many years of experience as a leader in what he calls the "truly formidable" development of vehicles of air transportation in the past 25 years.

He has made, I believe, a realistic appraisal of trends based upon that experience, and I am sure that his conclusions will be of great assistance to those, both in industry and government, who must plan far in advance

to assure the orderly integration of rapid technical changes in our air transportation system.

The overall impression this paper makes is good, but one phrase used by the author is debatable. He says that "the inherent conservatism of an engineer makes him a disappointing prophet."

On the contrary, if we realize but a few of the ideas dangled here before our eyes for improvement and progress, we will be able to classify Mr. Littlewood as an optimistic and productive prophet.

The paper provides an excellent treatment of the fundamentals of the aircraft: its dimensions, weights, power and thrust loadings, the aircraft activity factor, and the maintenance information, all of which have aided the author in his skillful analysis of the interrelation of the many complex factors that go to make up civil air-transport operation.

It is extremely encouraging to us in C.A.A. to see Mr. Littlewood's emphasis on those things that help to provide built-in safety in the vehicle itself. These include the "fail-safe" philosophy of design, simplicity, accessibility for inspection, accessibility for maintenance, and standardization of elements.

Adoption of these principles in the aircraft, in the design and construction stages, are tremendous aids in obtaining and maintaining the highest practicable degree of safety in operation.

We also feel that the principle of planned growth, to my knowledge first clearly stated here by Mr. Littlewood, is an excellent one. So far, the growth in our aircraft has come about more through expediency than by original planning, but if our designers can anticipate in their new transports the growth trends, then there will be substantial gains in safety and economy by so doing.

Nor have I seen elsewhere the idea of safety engineering so well presented. The idea of having this kind of engineering talent represented by specialists rather than making it a sort of overlay of the work of all other specialists should pay off. Safety deserves a "cabinet position" in aircraft design.

Mr. Littlewood has also pointed up the importance of problems that are of vital importance to us in C.A.A., problems that are with us today or that we must face later, such as noise, fatigue in aircraft structures, precision in reporting ceilings and visibility, complexity of electronic installations, safety in use of pressurized cabins, gust alleviation, better cockpit arrangements, approach and climb-out performance flexibility, good deceleration of jet aircraft, assurance against turbine wheel failure, the magnitude of fuel reserves, and others. Much work must be done on these problems even though considerable work has already been done.

In discussing the necessity for simpler aircraft, the author is especially vocal. His admonition, "Be on the offensive in the interest of simplification," supplemented by the wry comment, "No one, apparently, is devoted to taking things off" (the modern aircraft), has the virtue of being completely true and pleasantly rememberable. We can all hope he is an accurate prophet here.

The author has touched on the subjects of collision, traffic density, more precisely controlled flight paths, radar and electronic complexity. C.A.A., through its work in the Offices of Federal Airways and Aviation Safety, the Air Navigation Development Board, the Air Coordinating Committee, the Development Center at Indianapolis, and elsewhere, is working actively to bring through the development and test stages, and into use better, safer, and more economical equipment and procedures.

I should like to supplement, in one respect, Mr. Littlewood's plea for American industry to press on with the development of new and better aircraft. I feel that our civil industry will also have to take a greater hand directly in power-plant development itself.

Traditionally, the military services have developed our large power plants, and a great measure of our excellent record in transports stems from the work done many years ago in our military services, particularly in the Navy, in pressing the development of air-cooled radial engines. These were, in turn, refined and improved in air-line operation to the ultimate benefit of both military and civil users. Military design trends are now going in the direction of tremendous power outputs per unit and also in the direction of supersonic speeds. As Mr. Littlewood has indicated, we probably will have no new piston-engine-type developments. Therefore, except for such development as the military may do for power plants for personnel and cargo transports, our civil industry will be left, in the future, to develop its own power plants.

I believe it is particularly important that industry make special efforts in power-plant design and construction to reduce the outside noise that many citizens are complaining about so vociferously. I feel that Mr. Littlewood has given us some constructive thinking with respect to developments in turbine-powered aircraft. The matters he has discussed and the problems that he posed were among the factors that led to our recent decision in C.A.A. to establish a Turbine-Powered Transport Evaluation Team. Our objectives are to provide specialized training and information to the members, to assure uniformity of handling of turbine-powered aircraft projects, and to provide a central source of information and knowledge in this rapidly developing and important field.

Several years will probably pass before U.S.-built jet transports go into scheduled passenger service. By then our British friends should have several dozen jet transports in service and years of air-line service will have been logged on some of these aircraft. This is a tremendous advantage, and there will be great pressure to get our own new transports into service.

However, we have much to learn in design, in operation, in airway aids, and in airports before we can use new transports safely and economically. We have

hopes that funds will become available to the C.A.A. under Public Law 867, the so-called prototype testing law which is now on the books, to accelerate the work that industry and Government must do to determine the necessary answers.

I believe Mr. Littlewood's paper is a valuable contribution to aviation.

Jerome Lederer, Director, Flight Safety Foundation, Inc.: My predecessors have adequately dealt with the technical phases of Mr. Littlewood's superb presentation. I am on the program presumably to discuss this paper from the standpoint of his deep interest in safety. I appreciate this invitation for the significance it gives to safety and for the opportunity to support Mr. Littlewood's contentions.

Safety is woven all through the paper. It is worth noting that Mr. Littlewood seldom mentions safety without also referring either to economy or efficiency. The safe way of doing a job is usually in the long run also an economic and efficient way to do it. Safety is not solely a way to save lives and to prevent suffering. It is also a way to stimulate the creation of new wealth and to conserve the wealth we already have.

No one to my knowledge has developed a yardstick for measuring safety that is acceptable to varying interests. Everyone is for safety just as everyone is against sin and for virtue. But expediency and temptation often weaken our will to be virtuous.

Strangely enough the world "safety," except in its absolute sense of freedom from danger, means different things to different people:

To the airline passenger it means absence of anxiety.

To the manufacturers, safety often means an interference with the production line or reduced range and pay load.

To the Vice-President in Charge of Air Line Public Relations safety is a word that should seldom be mentioned above a whisper.

To the lawyer it means that his wife has to get along with last year's mink!

To the Editor of a newspaper, aviation safety is something to be hidden on the last page, along with railroad accidents.

To us in aviation, safety means the public acceptance and support of air transportation.

Mr. Littlewood's paper indicates, in strong terms, and often in the form of a plea, what safety should mean to the engineer.

He says it is the "prime duty of the engineer to simplify the tasks '(of the crew)' so that more can be accomplished with improved safety and efficiency." He criticizes engineers for their tendency to minimize reserve fuel requirements and other essential factors that cut into range or pay load, and he calls attention to the engineer's negative responses to safety suggestions. He sees little reason why suitable engineering action should not be taken to provide improved crash survival. He calls attention to the false hope of depending on service manuals for complete and adequate maintenance, and he appeals for advanced engineering thinking as the only guaranteed preventive of innumerable accidents and mishaps in relation to servicing and maintenance of aircraft. He declares that "all too often details of thoughtless design are discovered as the causes of incidents and accidents" in relation to hinges, valves, controls. He stresses repeatedly the need to design so that failure of a component will not create additional or cumulative hazards (the "fail-safe" concept) and he poses all this as a challenge to the quality and capacity of air-transport design engineering.

These are serious reflections on the design engineer and his interest in safety. I agree with Mr. Littlewood, but the engineer is probably less to be blamed than our educational system and, until recently, than the managers of industry. The implications and importance of safety, of always designing with the user in mind, have seldom been fully explained and properly interpreted to the engineer. Emphasis has been on performance. A well-known professor of aeronautics has declared that "safety, per se, was a relatively new concept in engineering curricula, not too seriously considered, if ever, by many instructors. If the industry wants safety consciousness or safety attitudes inculcated into the engineer, industry, which hires the product, must put the pressure on the colleges."

This paper points to the kind of pressure that is needed. The industry has not demanded safety and reliability with the same persistence as it has demanded performance.

Where Mr. Littlewood criticizes lack of simplicity, lack of standardization, the need for analysis of crew function, the need for simple ways and tools to maintain aircraft, he is getting into the new field of human engineering. It is gratifying to know that several manufacturers have already recognized the importance of applying proved psychological and physiological principles to the design of cockpits; they are calling on the human engineer to avoid inhuman engineering. Unfortunately, not many people are qualified in this new science; many engineers do not know it exists or do not recognize its significance. A vast educational and re-educational job needs to be done.

There is no time to comment on the many technical items that Mr. Littlewood discusses, such as high-density aircraft, fatigue, crash survival, but I just want to mention the high-wing versus low-wing, and the castoring undercarriage. I agree with Mr. Littlewood's statements, but I do not think that he meant that the book should be completely closed on those topics. Some airplanes must have high wings. Flying boats and amphibians, for example, and high-winged seaplanes are preferable to low-winged designs for certain types of bush operations and to clear docks and other obstructions. We should not abandon the idea that high-winged aircraft cannot be designed with greater safety

than they have had in the past. Similarly, we should not close our minds to the castoring undercarriage. There undoubtedly will be designs where they will be very desirable.

On the matter of manuals, the size and number of the maintenance and operation manuals is a good index to the number of booby traps in the design. If the designer lacks time to make it simple, and very often this is admittedly not feasible, he just adds another page to the manual. His technical education plays him false; he feels that because he cherishes his college textbooks and has learned to develop his knowledge by reading, that everyone else in aviation, the pilot and the mechanic, is conditioned in the same way. This is simply not so; the manuals often remain unread.

Mr. Littlewood discusses the place and importance of the safety engineering unit in an aircraft engineering organization. Under the stimulus received from the Directorate of Flight Safety Research, U.S.A.F., there is a strong trend in this direction—independent safety specialists reporting to high authority. Two aircraft manufacturers established such units several years ago; others are following. By critical review of design, these safety units tend to offset hazards introduced by inexperienced designers, by production managers who rightfully think only in terms of production efficiency, and by sales managers who exert pressure to meet a deadline which perhaps a year later results in a fatal accident.

These safety specialists, if they report to top management, act as a rallying point for safety conscious employees who are not often in a position to bring their criticisms or ideas to the attention of top management. And they are becoming especially valuable to industry by educating engineers on the constant need to think of the design in terms of the other man—i.e., the pilot, the mechanics, and last, but not lest, the passenger.

Maynard L. Pennell, Senior Project Engineer (Jet Transport Project), Seattle Division, Boeing Airplane Company: It is a real pleasure to comment on Mr. Littlewood's lecture because it is a subject in which I am greatly interested and because the paper itself deals with this subject in a thoroughly understandable and down-to-earth fashion.

Many of us in the industry are given a real thrill when we are reminded that we have participated to a greater or lesser extent in essentially the entire life of the air transportation industry. In retrospect 25 years does not seem to be such a long time. To say that many of us foresaw the tremendous growth of the air transportation industry would, I fear, be giving us considerable credit we do not deserve. However, I do remember the winter and spring of 1933 when the first Boeing 247's were taking shape at Plant I. There was a real thrill of enthusiasm throughout the Boeing organization, for here was a transport, the first of its kind, which would really set the air transportation industry firmly on its feet. I hope that we have a considerable amount of this same type of enthusiasm still abroad in our manufacturing organizations today.

The first part of Mr. Littlewood's paper is largely historical, and it would be most presumptuous on my part to attempt to add further to what he has said. In fact I find myself in such complete agreement with the entire paper that I found it somewhat difficult to choose items that I consider sufficiently controversial to deserve comment.

Mr. Littlewood makes a plea that we design more crash resistance into our transports. It has been said by others that airplanes should be designed to fly, not to crash, which I think is basically correct; however, it is probable that we can do a better job with respect to crash resistance than we have done in the past without serious compromise to the ability to fly. Whether or not we can live up to Mr. Littlewood's expectations that a well-designed and fitted airplane would readily permit its human occupants to survive a 25g crash is rather questionable to me. However, this depends on the definition of a 25g crash. It would probably be unnecessary to design seats that would withstand a 25g loading in any direction in static test, and I am sure that seats that live up to this standard cannot be designed without considerable weight compromise and, hence, economic compromise. Certainly our desire to withstand 25g on all items in the inhabited area of the airplane must be tempered by good engineering judgment. However, the essential part of what Mr. Littlewood had in mind can probably be accomplished by designing sufficient resilience, as well as a moderate amount of additional strength, into carefully selected components of our airplanes.

Mr. Littlewood also urges the design engineer to consider the servicing problems created by our admittedly complicated airplanes. He also comments on details of thoughtless design which are discovered as causes of accidents. Most of us know of such instances, some from our own direct experience and possibly I'm a little sensitive on the subject. In any case, I would like to say one or two words in defense of our efforts. The aeronautical engineer faces a variety of design conditions encountered in no other type of equipment. Temperatures from +160 to −100°F., air pressures that vary in the ratios of 10 to 1 from sea level to 50,000 ft., weight control to an extent not even considered in any other form of engineering, reliability requirements that are more severe than in most other applications, since frequently the lives of many passengers are involved—all these factors tend to make the designer's job more difficult. Then, in addition, he has to attempt to design in such a manner that maintenance can always be properly accomplished by the average mechanic. Here we often find ourselves hopelessly outnumbered. We can outguess the actions of 99 of the people who will service our airplanes, but the other 1 in 100 with diabolical cleverness devises some method of servicing

which the design engineer did not allow for. In retrospect it may appear obvious that we should have allowed for it. We hope to do better on each successive airplane and I think that we do in most respects. If, in spite of our best efforts, we still appear stupid at times, I can assure the world that it is not because we enjoy the reputation.

The suggestion that we establish within our organization safety experts who will make a critical review of a design from the standpoint of safety is worthy of careful consideration. We are doing this on an increasing scale within Boeing and have a small staff of engineers who devote their entire attention to this important subject. However, I hardly need remind you that safety is involved in so much of the design that a large staff of experts would be required if all matters affecting safety were to be reviewed in sufficient detail so that these experts could vouch for the integrity of the design. Such a duplication of effort is neither necessary nor desirable, as I'm sure Mr. Littlewood would agree. Hence, the principal responsibility for safety must remain where it has always been—with the designers themselves. I would be remiss if I were to leave this important subject without giving credit to the efforts of Jerry Lederer and the Flight Safety Foundation who have done much to make the entire industry more safety conscious and to provide valuable suggestions on specific methods of improving safety. We have also instituted within Boeing a series of Design Tip Sheets which point out mistakes on our own and other manufacturer's airplanes which have affected safety, in the hope that we can avoid repetition of such errors on future airplanes. The sum total of all these efforts is bound to result in improving designs from a safety standpoint, which is an objective we all sincerely hope to achieve.

With respect to the structure, I think the question of tear resistance and location of failures deserves some comment. In my opinion there is much that we can do to ensure that the failures that are bound to occur as a result of excessive loads during a crash or following certain catastrophic types of engine failure take place in such locations that the safety of the entire airplane is jeopardized to the minimum extent possible. It is obviously impossible to anticipate all the directions and magnitudes of loads which will be encountered under such conditions, but certain typical occurrences can and should be accounted for. For instance, the loss of an engine or of a main gear should not cause failure of the primary wing structure of rupture of fuel tanks. Some improvement is also possible with respect to tear resistance and limiting the extent of damage in instances of failure. If I may be permitted a somewhat facetious comment with respect to the incident on the DC-6 over Denver, it seems that the most obvious principle with respect to future design which can be drawn from that occurrence is that one should leave off the propeller in the first place. More seriously again, it seems that we may have the problem of explosive types of failure of the rotating parts within a jet or turboprop engine, although very real progress has been made in the direction of eliminating turbine wheel failures that plagued the early jet engines. We cannot yet entirely eliminate this type of failure from our thinking, and the design should take the best possible account of the results of such failures.

The comment above regarding deletion of propellers leads directly to my next comment, which has to do with simplification. We have in the jet transport our first major opportunity in a number of years to reverse the trend toward increased complexity. In fact a prototype jet transport is almost unaccountably simple in comparison with the airplanes to which we have become accustomed. One cannot get the thought out of his mind that there must be several major items that have been completely forgotten. I can only hope that even after satisfying customer requests the airplane may continue to exhibit much of this important characteristic.

Turning now to the design of future transports, I agree with all that Mr. Littlewood has said with respect to the difficulty of designing and operating aircraft for the shorter ranges of operation on a sound economic basis using present standards of cents per ton-mile. In fact, I have often wondered why we do not admit the higher cost and charge more for this type of service, since there are so many factors tending to make it well nigh impossible to keep expenses down to desired values. Regarding the airplanes to be designed for this type of service, I would like to add that I for one have not eliminated the possibility of a small jet transport for this application, even though it has often been said by others that the turboprop is most logical for this use. The basic simplicity of jets may be gain enough to offset their much-publicized disadvantages.

Turning to the problem of noise, I am sure that this is a subject that deserves much thoughtful consideration by all of us. Noise levels from jet engines are high, and with the increased thrust ratings of newer engines, apparently the problem will increase. To find the complete solution to this problem will probably require a resort to basic research—a long-term process. In the meantime there are certain factors that work in our behalf, one being the fact that the noise, once people become accustomed to it, is probably of a less annoying sort than that emanated from a piston engine and propeller combination and, two, with there no longer being any need for warmup and checking of "mags," etc., it can be hoped that the high noise level will be of comparatively brief duration and only associated with the take-off run and initial climb. Since the noise is fairly directional, this should mean that a person on a particular spot is not subjected to the noise long enough to have it of serious consequence. This is not to say that the operators do not need to look forward to installation of noise suppressors in areas where they are making frequent engine checks on the ground. But in spite of all

this, I agree heartily that noise is today, and probably will be for some time, a serious problem associated with jet airplane operation.

Concerning the problem of climb-out and approach paths in the vicinity of congested airports, I would like to say that in my opinion a properly designed jet transport will be able to fly exactly the same paths as today's reciprocating engine airplanes. It can, however, climb more steeply and at a higher rate of speed, and it will want to do so for efficiency if it is not limited by a coexistence with some of today's airplanes which by comparison are "clunkers."

The descent and landing of a properly designed jet transport should not impose severe problems. This assumes, of course, that such a transport has ample wing area, efficient high lift devices plus adequate and controllable drag devices, and engines that will accelerate rapidly from low power to full thrust in the event a go-around becomes necessary. All this is well within our grasp today. I do feel considerable concern over the problem of icy runways with jet transports. In this one respect, reversible-pitch propellers probably make a significant contribution to safety. Improvements of a different nature such as the tricycle gear, antiskid devices for brakes, and possibly the use of a parachute may provide equivalent safety for a jet transport. Only experience can tell.

Although I agree with Mr. Littlewood that a satisfactory reverse thrust producing device for jet aircraft is highly desirable, there is no promise of one in the near future so far as I know, and to assume that the satisfactory operation of jet transports should wait for the development of such a device is, of course, out of the question. Therefore, the initial jet transports must be designed to operate safety and economically without benefit of such a device, and I for one am confident that this is entirely possible.

With respect to the inherent problems of a jet power plant, experience to date encourages me to hope that there is less likelihood of catastrophic types of failures than with the present reciprocating engine propeller combination. However, lest this hope not be realized completely in fact, Boeing has consistently used a pod type of engine installation which I believe will effectively insulate the rest of the airplane from the most serious effects of engine failure.

There is one final comment with respect to engine fuel consumption. The ratio of 2 to 1 between the fuel consumption in pounds per hour per pound of sea level thrust of a jet engine as compared to the pounds per equivalent horsepower hour of an improved turboprop power plant or the latest compound reciprocating engines is mentioned. It seems to me that a more significant comparison would be at cruise altitude and speed where the fuel consumption for the jet engine is only about 1.4 to 1.5 times that of the most advanced turboprop or compound engines that have been proposed, operating at their optimum conditions and with reasonable propeller efficiencies. Compared with today's reciprocating engines, this ratio becomes only about 1.25 to 1. When one considers the advantages in terms of reduced weight and drag which accrue through use of jet engines, this ratio of fuel consumption begins to look small indeed, and I wonder if we have not allowed ourselves to be scared by a hobgoblin.

In closing I would like to restate that I believe Mr. Littlewood's paper is an extremely valuable contribution to the subject of air transportation and might well be used by all of us as a text for the design of our next transports. In looking at the future many of us at Boeing hope that the management's recent announcement that we have been engaged for some time in the development of a company-financed jet transport is the very thing that Mr. Littlewood makes a plea for—namely, the reassertion of the pioneering spirit that has always characterized American industry. We feel certain that, with the sympathetic cooperation of the air lines and the other potential users of our jet transport, we shall re-establish on American shores the leadership in the air transportation industry.

Reply to Prepared Discussions

Mr. Littlewood: For two reasons I am greatly appreciative of the discussions of my 16th Wright Brothers Lecture prepared by W. T. Dickinson, Frank W. Fink, Charles Froesch, Col. Francis C. Gideon, Charles F. Horne, Jerome Lederer, William Lewis, and Maynard L. Pennell—first, because they have been so uniformly kind and considerate and, second, because they have contributed so much material to help the Lecture. I would like, however, to clarify a few statements made in the Lecture which apparently were not entirely clear.

Mr. Froesch seemed to feel that I would be happy with a 50 per cent average load factor. Nothing would make me more miserable. I did refer to the fact that in the early thirties some of best qualified individuals in the business were pessimistic about our ever being able to achieve a better than 50 per cent average load factor, and I endeavored to sound a warning against the too optimistic acceptance of current very high load factors obviously associated with a better than normal business condition. Somewhere between the two lies a sensible assumption to cope with the business uncertainties of the future, and I can find little wrong with the 60–65 per cent numbers that have been commonly used.

I can certainly also join enthusiastically in the hope that we may find it unnecessary to greatly increase runway lengths with the tremendous costs and

problems which such a program involves. I see nothing in the picture which necessitates any serious concern in this respect. There are many reasons why our aircraft of the future should have take-off and landing speeds not too far different from those currently in use. Certainly, from the safety point of view we well recognize that increases in take-off and landing speeds are in the unfavorable direction. Furthermore, in order to achieve a reasonable and efficient comingling of new transports with currently operating models, we must make every effort to preserve a reasonable similarity of take-off climb and approach landing performances. If we then can, and must, anticipate similar take-off and landing characteristics, we have no reason to fear a requirement for increased runway lengths, assuming, of course, that we can, and will, solve problems of accelerated-stop distances on take-off and deceleration on landing.

Another matter in which the Lecture was not apparently clear was the assumption that I have objections to all types of aircraft except low-wing monoplanes. One of my basic requirements for a safe passenger airplane is that there be interposed between the passenger load and the probable point of impact, in a survivable crash, sufficient structure to absorb a reasonable amount of impact energy or that the structure be strong enough to retain its integrity despite an unfavorable disposition of mass relative to the passenger load and the point of impact. It is not inconceivable that a high-wing airplane *could* be built with special shock-absorption provisions and perhaps very great strength of fuselage structure to give an approach to the effect desired. However, the normal high-wing airplane shows rather small adverse weight penalties even without any such provisions, and its efficiency would be very low, I am afraid, if such provisions were made. A mid-wing airplane with cargo disposed below the floor and wing level presents, I believe, a most happy combination of shock-absorbing capacity-weight distribution, as well as any safety advantages that can be claimed for a high-wing airplane in the nature of protection of fuel-tank locations and possible reduced tendency to ground loop. I have mentally classed such mid-wing airplanes with low-wing airplanes in achieving the desirable mass distribution. As far as boats are concerned, it is obvious that high-wing designs are not only admissable but essential, and for strictly cargo operations the low-loading advantages of the high-wing type are obvious for military and miscellaneous field operations, although I think they vanish substantially in a scheduled cargo operation where adequate and efficient loading provisions can be made at the terminals.

I also object mildly to the comment that I am "pessimistic" about helicopters for local scheduled operation. What I have tried to be is "realistic." I am reminded of the rather sage comment of a well-qualified engineer a few years ago to the effect that "helicopters do exactly what we want to be done but they do it in a gosh awful way." I am convinced that the helicopter, as an improved flying machine, will find a most valuable application in an integrated transportation system. There are problems to solve and substantial improvements to be made, but I would urge renewed efforts toward their early accomplishment.

I would also like to comment concerning aircraft operating noise, which is really an oversimplification of the whole subject of aircraft operating annoyances, which obviously includes the fear aspect to a substantial degree. However, it seems clear that, of all the elements of annoyance, noise is the one that, because of its intensity and constant repetition, tends to build up the psychological background for active resentment. I think it is a dangerous philosophy to accept the idea that people can, or will, become accustomed to high noise levels and will "think nothing of it." There does not appear to be any avoidance of our basic obligation to reduce substantially the annoyances of aircraft operations in the vicinity of airports, including noise as the most common irritant. Without rather basic corrections, we must look forward to an increased frequency and intensity of noise as our operations multiply and our units increase in size and power. Pending the ultimate and ideal solution of adequate reduction of noise at its source, we can, of course, help the situation by education and friendly public relations based on the sincere and honest assurances that we are doing everything that we can.

Mr. Fink comments that the industry, as a whole, should spend more time and effort on preventing crashes than on trying to prevent casualties in the event of a crash. I will certainly take no issue with this as a desirable principle, but I hesitate to assume that the industry is not doing all that it reasonably can to achieve this objective, and since common sense tells us that "accidents will happen," we have a supplementary obligation to minimize the seriousness of such accidents.

I would also agree with him that we would love to have suitably and adequately developed turboprop power plants and accessories to put to work as a next logical step in the performance trend of transport aircraft. It would solve many problems for us and would give ready answer to many questions and doubts as to the economics of jet operations. On the other hand, we do not have such power plants, and the time required to develop them to a condition of adequate reliability may well force the early development of jet transports which for suitable applications can, we believe, be made adequately efficient and economical.

Mr. Fink also points out that I made no reference to air cargo. This was not because of any lack of appreciation of its ultimate importance in air transporation but primarily because of a lack of space and time. There are many other phases of air transport which received almost as casual treatment for the same reasons.

I was gratified to learn from Mr. Johnson's comments

that "Constellation engines are designed to fall out of the airplane when on fire." I have known lots of other engines to fall out of airplanes because of fire or propeller failure whether they were designed with that in mind or not. On the other hand, the point I was trying to make was not whether the engine would fall out, but how it would fall out and what it would leave behind it in the way of a safe or unsafe condition.

Mr. Dickinson who looks forward in his comments to "many happy arguments in the days to come" accuses the lecturer of recommending simplification and simultaneously urging the inclusion of numerous additional provisions. I do not find anything too inconsistent in these recommendations. Simplification, to me, does not mean not doing things that should be done, but rather doing the things that should be done in the very best and easiest way. Certainly, progress requires that we continue to do more of the needed things, but simplification urges that we eliminate unnecessary duplication, that we combine units wherever possible without sacrifice of reliability, that we design inherent capacity to perform desirable functions without supplementary devices, and in short, that we do what needs to be done the very best way and, of course, avoid doing what does not need to be done. This has not always been the case in the past.

I must take issue with one minor suggestion in Mr. Horne's comments to the effect that "our civil industry will be left, in the future, to develop its own power plants." Desirable as this might be, I am afraid it is economically impractical and that, as in the past, industry will be dependent to a large degree on variations and developments from basic military models, or at least Federally-sponsored development projects. There are two reasons for this—one, that costs of such developments are very great, as well as time- and energy-consuming; and, two, that the industrial market for the product is too small to justify development costs. On the other hand, it is difficult to understand why the military services have not expressed a broader appreciation of needs in the turboprop and jet fields which would make available to industry power-plant sizes and types suitable for its use. It is almost axiomatic that any airplane that is suitable and efficient for commercial transport purposes would prove of inestimable value to the military in time of war. The formulation and implementation of a national policy with respect to aviation, including as the British do both military and civil aspects, would, I believe, clarify this picture appreciably and might well lead to the early development of additional power-plant units that would prove of inestimable value in both military and commercial uses. I am assuming, of course, that such could be accomplished without the throttling controls that always threaten to beset such a program.

In closing, I would like to again express my appreciation to the discussers, both formal and informal, who have added so much to the material and interest of the Lecture. I would also like to again express my thanks to Otto E. Kirchner for his multiple presentations of the Lecture and for the help he gave in its preparation and the value of his extemporaneous discussions.

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The Aerodynamic Profile as Acoustic Noise Generator

MAX KRAMER*

Coleman Engineering Company

SUMMARY

Everybody knows that fast-moving aerodynamic profiles, such as propeller blades, are about the noisiest thing on earth. This noise has been carefully studied in the past. The result was that propeller noise consists of two entirely different components. First, there is the rotational noise that is caused by the variation in distance of the pressure source from the observer. By nature, this noise is mainly emitted in the plane of rotation and contains strong peaks at the fundamental and the harmonics of the number of blades times the revolutions per second. This component of the noise has been theoretically investigated, and there is good agreement with measurements. Second, propeller noise consists of the profile noise or vortex noise. The profile noise is best heard near the axis of rotation, since there the rotational noise theoretically is zero. Explanations of the origin of this profile noise have often been attempted. However, even the most recent explanation fails to make understandable the outstanding role that the Mach Number plays.

The paper gives a recent explanation of profile noise, reports some new experiments on the matter, and, finally, states the author's opinion on the predominating source of profile noise.

A Recent Explanation of the Origin of Profile Noise

Reference 1 explains the generation of profile noise as follows: "The good profile radiates a broader frequency band (than the poor one). As explanation we might assume that the vortices (of the vortex stream leaving the profile) are generated in a kind of feedback mechanism. A vortex leaving the profile produces a disturbance in the air which travels with sound velocity to the front of the profile and steers the generation of the next vortex. In the case of a poor profile (depth $\approx$ thickness), the feedback is strong and the place where the next vortex starts is well defined. As a result we have a very stable vortex frequency. In the case of a good profile (depth > thickness), the feedback is not so strong (larger distance between front end and rear end), the place where the vortices start is not so stable, and a broader frequency band is radiated."

This explanation sounds logical as long as slow traveling speed of the profile is considered. But when it approaches sonic speed, any acoustic upstream feedback from the trailing edge to the leading edge is bound to fail. This, according to the explanation mentioned, would mean that the profile noise decreases with the approach of sonic speed. The opposite, a rapid growth of the profile noise with the approach of sonic speed, has always been measured.

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* Technical Director.

An Experimental Proof of the Independence of the Profile Noise from the Trailing-Edge Vortices

The boundary layer creates the vortices that leave the profile at the trailing edge. If there is no boundary layer at the trailing edge, no vortices leave the profile. Thus, boundary-layer removal should have greatly affected the profile noise in intensity and frequency if the explanation mentioned above were to hold true.

A single-blade propeller of 3-ft. radius was spun in a sound room. The blade consisted of a symmetrical profile of 12 per cent thickness, 1-in. profile depth at the tip, and 4-in. profile depth at the root. Provisions were made on the outer 15 per cent radius of the blade to suck off the boundary layer near the trailing edge of the profile. The blade spun at zero angle of attack. The flat response microphone of a sound level meter was mounted concentrically with the blade at a distance of 6 ft. from the blade. A pump could apply either suction or pressure to the duct inside the blade, which in turn was connected with the 200 holes of 0.04 in. diameter spread out over the outer end of the trailing edge.

The profile noise of this blade was measured in the Mach Number range from 0.1 to 0.4, with the holes sealed as well as open, the suction or pressure applied. The result was that neither suction nor pressure affected the profile noise measured before with the holes sealed.

This measurement, in the opinion of the author, made clear that the vortices at the trailing edge are not the primary cause of the profile noise. Thus, the real cause of profile noise still had to be found.

The Turbulence Ahead of the Profile as a Possible Cause

When pondering the possible cause of profile noise, one fact must be borne in mind. The noise pressure suddenly rises with the approach of sonic speed in a manner similar to that of the lift of a wing. Thus, it looked as if something were oscillating the angle of attack of the profile, thereby oscillating the lift and creating the noise. On a short solid steel blade that is not affected by wing flutter and is driven extremely

smoothly, one possible cause of angle-of-attack oscillation is the air turbulence ahead of the profile. With this basic concept in mind, several tests and calculations were carried out.

Two Sound-Room Tests on the Relation of Ambient Turbulence and Profile Noise

At zero thrust in the sound room, the blade ran in the wake created by its previous revolution. For this reason, a single blade of large radius and small profile depth was used in order to lower the disturbance due to the previous revolution. From aerodynamics we know that, at a ratio of profile depth to profile travel of approximately 200, the difference in air speed between the wake and the surrounding air has practically vanished, while the turbulence due to the wake can still be measured. By introducing a small angle of attack of the blade, it must be possible to displace this turbulent wake axially so that the blade no longer strikes the center of the turbulent wake of its previous revolution. Thus, if the concept of the air turbulence ahead of the profile as the cause of the profile noise were to hold true, small positive and negative angles of attack of the blade must lower the profile noise when compared with that at zero angle of attack. Naturally, great angles of attack would again make things worse, since a great thrust will cause additional turbulence when generated inside a sound room.

Two different blades were tested in the sound room, with the result that in both cases the profile noise was 3 db. lower when the angle of attack was $\pm 1°$ instead of zero. This effect is not very strong, but, as explained before, no great effect could be expected since the thrust sets up a new type of turbulence that limits the effectiveness of the wake displacement. The right measure would be to suck turbulence-free air axially through the sound room by means of an outside blower. This would permit zero thrust on the test specimen and yet remove the turbulence created by its previous revolutions.

The second sound-room test was to answer the question whether the concept of the turbulence, ahead of the profile, as a noise source would explain the sudden rise in noise pressure with the approach of sonic speed. For this the measurements of reference 1 were used, since they go up to Mach 0.8 while the available test stand was limited to Mach 0.6. Fig. 1 shows the result of the peak noise pressure measured as a function of the tip Mach Number (reference 1, Fig. 3). Fig. 1 also shows two dotted curves, called "laminar" and "turbulent." It may be explained how these theoretical curves were arrived at.

The average velocity vector of the turbulence ($\Delta\bar{v}$) created by the previous revolutions must be a function of the drag coefficient of the profile (C_D) and the spinning speed of the blade (v), or $\Delta\bar{v}$ is proportional to $C_D v$. This turbulence vector ($\Delta\bar{v}$) will create oscillations of the angle of attack of the profile with the average amplitude

$$\Delta\bar{\alpha} = \Delta\bar{v}/v$$

or $\Delta\bar{\alpha}$ is proportional to C_D. These oscillations of the angle of attack will induce oscillations of the profile lift, or an acoustic pressure P_{ac}, which is proportional to $C_D \times (dC_L/d\alpha)v^2$. In the laminar range of flow, C_D is propor-

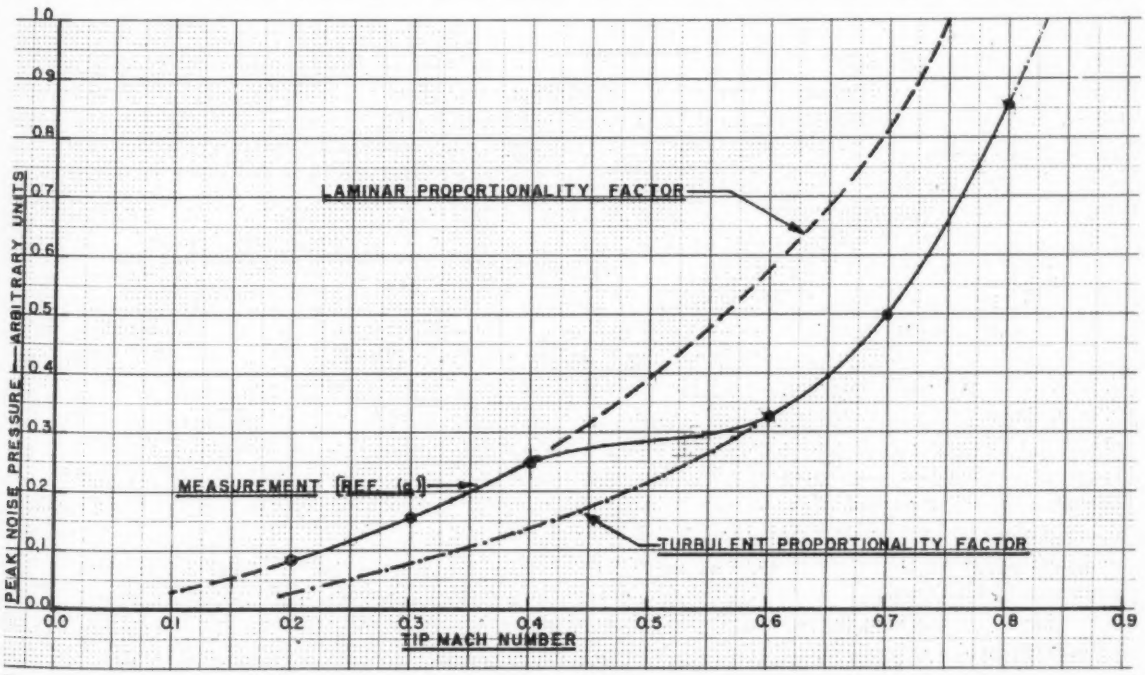

FIG. 1. Peak noise pressure of thrustless single-blade propeller vs. Mach Number. Note: "Ref. (a)" after the word "measurement" in the above figure should be "Ref. 1."

tional to $v^{-1/2}$. In the turbulent range of flow slightly above the transition, C_D = constant. The lift slope ($dC_L/d\alpha$) of the profile in the subsonic range is a function of Mach Number (M). $dC_L/d\alpha$ is proportional to $1/\sqrt{1-M^2}$. Replacing v by M we arrive at two proportionality factors of the noise pressure in the subsonic range: $P_{aclam.}$ is proportional to $M^{1.5}/\sqrt{1-M^2}$ and $P_{acturb.}$ is proportional to $M^2/\sqrt{1-M^2}$.

The dotted curves in Fig. 1 represent these two theoretical expressions. It can be seen that the dotted curves well match the corresponding ranges of the measurement. The transition from laminar to turbulent occurs at a tip Reynolds Number of 3×10^5, which is in good agreement with aerodynamic profile and propeller experience.

The results derived from sound-room tests made it seem probable that the turbulence ahead of the profile was causing the profile noise. This would mean that the profile noise in flight cannot be studied in a sound room, since the turbulence in a sound room and the turbulence encountered in flight are not necessarily equal.

A Profile Noise Measurement in Flight

Noise measurements on model propellers, such as reference 3, convey the impression that the rotational noise is predominating and that the profile noise is weak when compared with the rotational noise. This must not be true under actual flight conditions. (1) The model propellers are always acoustically studied under static conditions whereby the inner sections of the blades operate at reduced air speed, thus adding less to the total profile noise. (2) The much larger dimensions of full-size propellers shift the profile noise frequencies from the ultrasonic range[1] to the audio range, while the rotational noise frequencies, which on models cover the audio range,[3] shift toward the lower limit of the audio range. Thus, the profile noise under actual flight conditions may have much more bearing on the noise problem than is commonly realized. In order to clarify this situation the following flight measurement was carried out:

The flat response microphone of a sound level meter was mounted on top of a blimp. The installation of the microphone was acoustically checked for possible interference by the hull of the blimp. Since no such interference could be found, the blimp went up to 5,000-ft. altitude, cut its engines, and slowed down to approximately 15 m.p.h. An aircraft (F6F) passed overhead at full throttle, equal to 340 m.p.h. and at various relative altitudes of 300, 600, 1,200, 2,400, and 4,800 ft. At each relative altitude, the runs were repeated four to five times. The noise picked up during the passage of the aircraft was recorded and, later, frequency-analyzed in the laboratory with the aid of a panoramic frequency analyzer and a camera taking samples of the spectrum. The evaluation was concentrated upon the short period during which the aircraft was vertically overhead because in this position the signal is strongest, the true frequency is heard, and the range equals the altitude difference between the aircraft and the blimp. Naturally, the rate of frequency shift due to the Doppler effect is at a maximum during the passage. Thus, it had to be carefully considered how long a period of the noise record could be used for the frequency analysis. If a frequency shift of ±10 per cent is considered permissible, the useful duration is 0.25 sec. at 300-ft. relative altitude and 4.0 sec. at 4,800-ft. relative altitude. Since the panoramic analyzer sweeps at approximately 2 cycles per sec., the useful duration of the noise record was comparatively short at a 300-ft. range and ample at the 4,800-ft. range. Fortunately, the ambient noise level was so low that the 4,800-ft. signal was still 20 db. above the noise level.

The result of the frequency analysis was surprising. The noise covered almost evenly the range from 200 to 3,000 cycles per sec. at 300-ft. range and 200 to 1,000 cycles per sec. at 4,800-ft. range. At no range did the spectrum show the sharp peaks and dips that are characteristic of rotational noise. Thus, it was concluded that, under the specific conditions of this measurement, the profile noise must have been predominant. The center frequency measured at short range was approximately 780 cycles per sec.

The center frequency measured in flight made possible another check on the concept derived from the sound-room tests. In flight, the wake of the profile does not affect the turbulence ahead of the profile. Thus, in flight, the most reasonable assumption is that the atmospheric turbulence evenly covers all sizes of vortices. The question is which size vortices will cause the strongest lift oscillations and, thereby, determine the center frequency and the peak pressure of the noise spectrum. When assuming equal circumferential speed of all sizes of vortices, apparently the vortex with a diameter equal to the profile depth (D) adds most to the circulation about the profile and, therefore, creates the peak noise pressure. Since this vortex travels a distance equal to $2D$ from touching the leading edge to leaving the trailing edge and creates 1.5 cycles of lift oscillation during this travel, the center frequency should be approximately

$$Fr_{(\text{center})} = \frac{1.5 v_0}{2D} = 0.75 \frac{v_0}{D}$$

where v_0 is the air speed of the profile and D is the profile depth.

When applying this formula to the blimp-aircraft measurement, the center frequency measured equals that determined by the formula when the air speed and the profile depth at 80 per cent of the propeller radius are used. This is as close as an approximate formula and a single, though precise, measurement can come. The result again seems to support the idea that the

(*Concluded on page 296*)

Conical Potential Solutions in Linearized Supersonic Flow

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ABSTRACT

An important concept in the development of linearized supersonic flow theory is the conical flow theory originated by Busemann[2] wherein conical boundary value problems are considered in which the velocity components are conical. Attention is focused in this paper on strip-type boundary value problems in which the potential itself is conical. In application conical potential solutions are useful in the calculation of spanwise and chordwise lift distributions of twisted wings.

DISCUSSION

IN LINEARIZED INVISCID FLOW THEORY, the perturbation velocity potential is, in a sense, a more basic flow variable than the velocity components (or pressure). In linearized supersonic flow theory, this idea goes back to the original investigations of Volterra and Hadamard and in recent times to Evvard's method of solution[1] for supersonic flow problems for general planar systems. This seemingly philosophical point of view appears also to be true in application. In aerodynamic design the usual quantities of interest are integrated values (or ratios of them) such as lift, spanwise or chordwise lift distributions, moments, centers of pressures, etc., which are all obtained by integration of velocity components (or pressure) or moments of velocities over a surface or line. Thus the velocity potential (or the difference in the velocity potential at two points), which itself is an integral of velocity (or pressure), is a quantity of immediate interest.

An important concept in the development of linearized supersonic flow theory is the conical flow theory† originated by Busemann[2] and subsequently developed further and elaborated by several authors including Lagerstrom,[3] Hayes,[4] and Goldstein and Ward,[5] wherein conical boundary value problems are considered in which the velocity components are conical; the perturbation velocity potential, φ, which has the dimensions of velocity times length, is not conical; however, φ/z, where z = the free-stream coordinate, is conical. The present paper is limited to constructing solutions in which φ itself is conical and some additional related solutions of interest; the discussion is limited to planar systems. The mathematical question of uniqueness (at least in problems of the type considered in this paper) is settled by setting $\varphi = 0$ in the free stream.

First consider the conical flow solution for the conical boundary value problem shown in Fig. 1a. The solution in the plane of the wing in terms of the conical velocity components u (sidewash), v (upwash), and w (pressure component) is

$$u/W\alpha = (1/\pi)\ \text{sech}^{-1}|t|, \quad \text{for } |t| \leq 1 \tag{1a}$$

$$\left.\begin{aligned} v/W\alpha &= 0, \quad \text{for } x > 0 \\ &= 1, \quad \text{for } x < 0 \end{aligned}\right\} \tag{1b}$$

$$w/W\alpha = (1/\pi)\ \cos^{-1}t \tag{1c}$$

where W = free-stream velocity, $\beta = \sqrt{M^2 - 1} = \text{cotn}^{-1}\ \mu$, μ = Mach angle measured from the free-stream direction, and $t = \beta x/z$, the conical variable. Then the potential $\delta\varphi$ for the boundary value problem shown in Fig. 1b is immediately obtained by differentiating the velocity potential φ (for the conical flow problem, Fig. 1a) with respect to x (giving the sidewash u for the problem in Fig. 1a); thus,

$$\delta\varphi \equiv (\delta\xi)\cdot u \tag{2a}$$

where u is given by Eq. (1a) and, hence,

$$\delta\varphi/W\alpha = (\delta\xi/\pi)\ \text{sech}^{-1}|t| \tag{2b}$$

The conical nature of the potential solution given by Eq. (2b) is pointed out by Bleviss in reference 7. But the immediate consequence of Eq. (2a) is that now every conical flow solution generates a *conical potential solution* for a problem with the same external plan form but with *strip-type*‡ boundary conditions.

It is of interest to compare the conical potential problem (Fig. 1b) to the corresponding conical flow-strip problem (Fig. 1c); the difference between the two problems is that the conical potential problem is constructed by line source (or doublet) distributions of constant strength and the conical flow-strip problem, by line source distributions of source strength directly proportional to z. This immediately yields another way

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† A further important development is generalized conical flow theory, for example, by Germain,[6] wherein the property of homogeneity of the wave equation and boundary conditions is considered in more general form.

‡ Note that the strip is not restricted to the free-stream direction and the conical flow problem does not necessarily have to be planar.

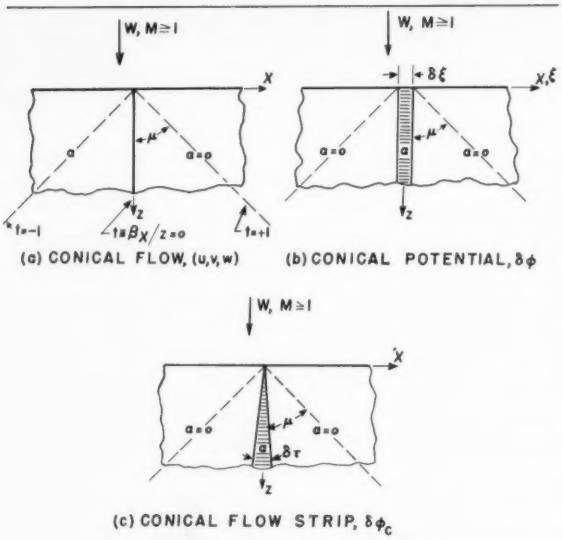

FIG. 1. Supersonic leading-edge solution.

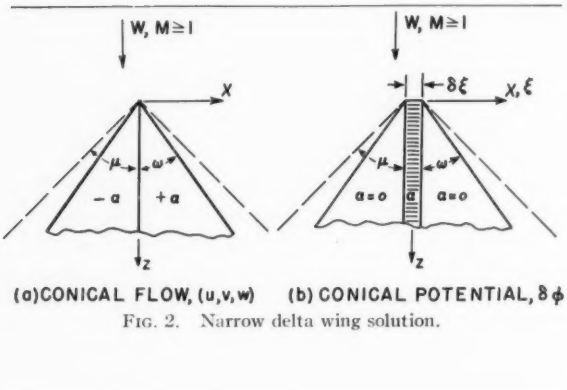

FIG. 2. Narrow delta wing solution.

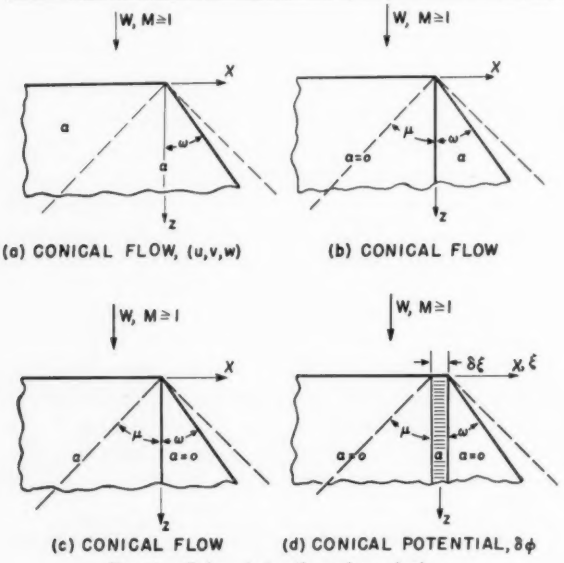

FIG. 3. Subsonic leading-edge solution.

of generating conical potential solutions:* solve the corresponding conical flow-strip problem, e.g., in the manner of Brown,[8] for the potential $\delta\varphi_c$; then

$$\delta\varphi = \delta\varphi_c/z \tag{3}$$

Clearly, a third way of obtaining conical potential solutions is by Evvard's method.

Conical potential solutions immediately applicable to desired physical problems are not always directly obtainable from corresponding conical flow problems such as in Fig. 1. For example, consider the conical potential problem shown in Fig. 2b. The solution is not directly equal to the sidewash u for the problem shown in Fig. 2a, but by inspection the required solution is the part of u which does not have the leading edge singularity. It is clear why this is so, since the sidewash u (Fig. 2a) must be the conical potential solution for the problem in which there is not only a nonzero centerline strip as in Fig. 2b but in addition nonzero leading edge strips. This is most easily illustrated by considering the problem with one subsonic leading edge (Fig. 3). The conical potential solution for the problem shown in Fig. 3d is easily calculated by Evvard's method:

$$\delta\varphi/W\alpha = (\delta\xi/\pi)\,\mathrm{sech}^{-1}\left|\frac{(1+m)t}{2m-(1-m)t}\right| \tag{3a}$$

for $|t| \leq 1$, where

$$m = \beta \tan\omega$$

The sidewash u_a (Fig. 3a) is

$$u_a/W\alpha = -[2/\pi(1+m)]\cdot[m(1+t)/(m-t)]^{1/2} \tag{3b}$$

The sidewash u_b (Fig. 3b) is

$$u_b/W\alpha = (1/\pi)\left\{-[2/(1+m)]\times [m(1+t)/(m-t)]^{1/2} - \mathrm{sech}^{-1}\left|\frac{(1+m)t}{2m-(1-m)t}\right|\right\} \tag{3c}$$

Hence the sidewash u_c (Fig. 3c) is, by superposition

$$\left.\begin{aligned} u_c/W\alpha &= (1/\pi)\cdot\mathrm{sech}^{-1}\left|\frac{(1+m)t}{2m-(1-m)t}\right| \\ &\equiv (\delta\varphi/W\alpha\cdot\delta\xi) \end{aligned}\right\} \tag{3d}$$

In the same way for the narrow delta (Fig. 2)

$$u/W\alpha = -(2/\pi)[(1-\bar{l}^2)^{-1/2} - \mathrm{sech}^{-1}|\bar{l}|] \tag{4a}$$

$$\delta\varphi/W\alpha = (\delta\xi/\pi)\,\mathrm{sech}^{-1}|\bar{l}| \tag{4b}$$

for an α strip and $|\bar{l}| \leq 1$, where $\bar{l} = (x/s)$ and s = semispan for given z (see Fig. 2b).

The interesting result to be noticed in Eq. (4b) is that the conical potential solution for the narrow delta with

*Or the conical potential problem itself can be considered as a two-dimensional Laplace potential problem by a Chaplygin transformation analogous to conical flow problems.

nonzero centerline strip (Fig. 2b) is a function only of the ratio (x/s) and equal to the "slender-body theory" result.

Concentrating attention on the potential $\delta\varphi$ of other strip problems, which are not conical in the usual sense, is also of interest. One example is shown in Fig. 4a. $\delta\varphi$ is conical (vertex at the origin) in region I and given by Eq. (2b). In region II, $\delta\varphi$ is also conical but with vertex at the intersection of the upstream projection of the strip and the leading edge $(x, z) = (0, -\beta s_0/m)$. Thus in region II [cf. Eq. (3a)]

$$\delta\varphi/W\alpha = (\delta\xi/\pi)\ \mathrm{sech}^{-1}\left|\frac{(1+m)t'}{2m-(1-m)t'}\right| \qquad (5a)$$

where $t' = \beta x/(z + \beta s_0/m)$ is the conical coordinate from $(x, z) = (0, -\beta s_0/m)$.

Eq. (5a) reduces for the case of the rectangular side edge (Fig. 4b) to (in region II)

$$\delta\varphi/W\alpha = (\delta\xi/\pi)\ \mathrm{sech}^{-1}\left|\frac{(x/s_0)}{2-(x/s_0)}\right| \qquad (5b)$$

Eq. (5b) states that $\delta\varphi$ is independent of z in region II; hence, the pressure is zero there. Application of some of the foregoing conical potential (and modified) solutions are found in reference 9.

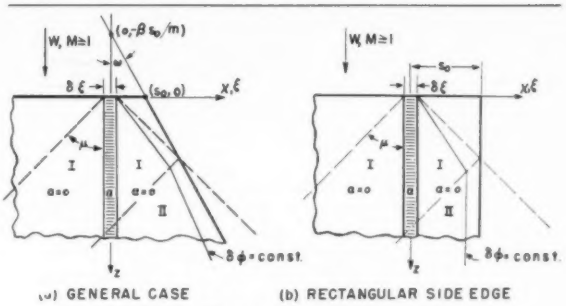

FIG. 4. Modified conical potential solution.

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A Simplified Formulation of the Similarity Concepts in Isotropic Turbulence

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January 19, 1953

IN THE DISCUSSION of the similarity concepts in isotropic turbulence, three cases of self-preservation are discussed by von Kármán and Lin,[1, 2] together with their physical interpretation. In the present note, these cases of self-preservation are obtained in a simple manner from dimensional arguments, which also indicate other possibilities.

One essential point in the similarity concepts developed in references 1 and 2 is the existence of *four* parameters for the characterization of homogenous isotropic turbulence. These four parameters are denoted by ν, ϵ, D, and J_0, and their role in the various frequency ranges is discussed. (See Table I, reference 2.) Instead of the above parameters, we may use the velocity and length scales V and L, and the following two constants of the problem: the kinematic viscosity ν and the Loitsiansky's invarient J_0. These can be combined into dimensionless ratios in the form of the Reynolds Number

$$R = VL/\nu \tag{1}$$

and the parameter

$$S = V^2L^5/J_0 \tag{2}$$

The spectrum function is then of the form

$$F = V^2Lf(kL, R, S) \tag{3}$$

Unless there are other constants of the problem, it may be conjectured that Eq. (4) represents an idealized *universal* form of the spectrum. Actual realization of this idealized form, however, may not be complete in usual experiments.

It is easy to record the connection between the parameters appearing in Eq. (3) and those used in reference 2. The velocity and length scales V and L are given in Table I[2] as

$$\left.\begin{aligned} L &= (D^3/\epsilon)^{1/4} \\ V &= (D/\epsilon)^{1/4} \end{aligned}\right\} \tag{4}$$

The other velocity and length scales (v, η) and (V^*, L^*) defined there stand in the following ratios to (V, L):

$$v/V = R^{-1/4}, \qquad \eta/L = R^{-3/4} \tag{5}$$

$$V^*/V = S^{1/3}, \qquad L^*/L = S^{-1/3} \tag{6}$$

It is clear from Eq. (3) that strict self-preservation is possible only when both R and S remain constant during the process of decay. This is clearly impossible if V and L are changing. Thus, self-preservation is bound to be an approximation.

If S *is constant* in Eq. (3) and R is either so small or so large that its variation produces little influence on the spectrum, approximate self-preservation holds. Thus, we have: *Case* (*a*) R small, S = constant; *Case* (*b*) R large, S = constant.

On the other hand, if R *is constant* and S is either very small or very large, approximate self-preservation also holds. Thus, we have: *Case* (*c*) R = constant, S small; *Case* (*d*) R = constant, S large.

Case (a) is the case of small Reynolds Numbers, applicable to the final period of decay. Case (b) is the case of nonviscous similarity at large Reynolds Numbers. Case (c) is applicable to the early stage of the decay process and was characterized in references 1 and 2 by $\eta/L = R^{-3/4}$ = constant. The approximation $S \to 0$ was expressed by the neglect of the low-frequency components from the self-preservation hypothesis (cf. reference 3).

The designations (a), (b), (c) are the same as those used in reference 1. Case (d) is not covered by previous discussions, but its physical interpretation is obscure.

It appears from the above discussions that under the combination of the conditions large R and small S, approximate self-preservation may also be possible. In such a case, one obtains a power law for the variation of V and L, but the exact value of that power is not determined. This reverts to the original discussion of von Kármán (cf. reference 4).

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Structural Modifications in Redundant Structures

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December 19, 1952

IN HIS INTERESTING REVIEW of methods of analysis for swept-wing structures, Williams[1] emphasizes the need for a simple method of evaluating the changes in deflection and stress due to small structural modifications. It can be agreed that such a method is a nearly indispensable tool, mainly in investigations where the aim is to reach the optimum solution of a structural problem. Fortunately, however, it can be stated that a simple and powerful method for this purpose has been available for a few years.

As far as the authors are aware, the principle underlying this method is due to Best,[2, 3] and it has again been mentioned by the senior author. The method seems to have been overlooked by many investigators, as well as by stress engineers. Meanwhile

the method has proved its power in practical application, and it seems worth while to recall it in this brief note.

The principle can be described in the following way. Consider an indeterminate structure, for instance a truss, under a specified load. The cross-sectional area of one simple bar of this structure is modified with respect to the original shape of the truss, for which the indeterminate analysis was performed.

Now the cross section of the modified bar is supposed to be reduced again to its original area. *The structure as a whole, however, is not allowed to alter its deformations and, hence, its stresses.* This condition can be reached by adding to the true external load *a virtual load, equal and opposite to that resulting from the stresses in the material removed.* Consequently, *the stresses and deformations in the modified structure under the specified load are exactly identical with those in the original structure under the specified and the virtual load combined.*

Let the load in the bar involved be L_0 in the original and L_m in the modified structure; the corresponding cross-sectional areas, A_0 and A_m; and the virtual load, mentioned above, ΔL. Because of the redundancy of the structure, only a fraction $1 - \eta$ (where $0 < \eta < 1$) of this virtual load will act upon the bar under consideration. The quantity η thus designates the fraction of the load ΔL, carried by the nondirect connection between the ends of the modified element. The magnitude of η is easily determined once the matrix of the indeterminate analysis of the original structure is known and solved.[4] The following relations now can be put forward:

$$\frac{L_m}{A_m} = \frac{L_0 + (1 - \eta)\Delta L}{A_0} = \frac{-\Delta L}{A_m - A_0} \tag{1}$$

From the outer members of Eq. (1) follows

$$\Delta L = L_m \frac{A_0 - A_m}{A_m} = (\lambda - 1)L_m \tag{2}$$

where

$$\lambda = A_0/A_m \tag{3}$$

Substituting Eqs. (2) and (3) into the left-hand members of Eq. (1) leads to

$$\begin{aligned} L_m\lambda &= L_0 + (1 - \eta)(\lambda - 1)L_m \\ L_m[1 - \eta(1 - \lambda)] &= L_0 \end{aligned} \tag{4}$$

where η, λ, and L_0 are known quantities.

A generalization of this procedure if more than one member is modified is easily established. Eq. (1) then reads

$$\frac{L_{m_i}}{A_{m_i}} = \frac{L_{0i} - \sum_k \eta_{ik}\Delta L_k + \Delta L_i}{A_{0_i}} = \frac{-\Delta L_i}{A_{m_i} - A_{0_i}} \tag{5}$$

where i designates a station and k a modified element.

Solving for ΔL_i and substituting into the left-hand members leads to

$$\begin{aligned} L_{m_i}\lambda_i &= L_{0i} - \sum_k \eta_{ik}(\lambda_k - 1)L_{mk} + (\lambda_i - 1)L_{mi} \\ L_{m_i} &- \sum_k \eta_{ik}(1 - \lambda_k)L_{mk} = L_{0i} \end{aligned} \tag{6}$$

Eq. (6) represents a set of n simultaneous equations where n is the total number of modified elements k. The subscript i designates the number of the equation. Prior to the application of Eq. (6), the quantities η_{ik} (the loads at the stations i from negative unit loads in the elements k) must be determined from the matrix of the original structure.[4] All modified elements must also be introduced as a station. The loads L_{m_j} at nonmodified stations of the modified structure are computed from

$$L_{m_j} = L_{0j} + \sum_k \eta_{jk}(1 - \lambda_k)L_{mk} \tag{7}$$

where the quantities η_{j_k} have to be determined as indicated above.

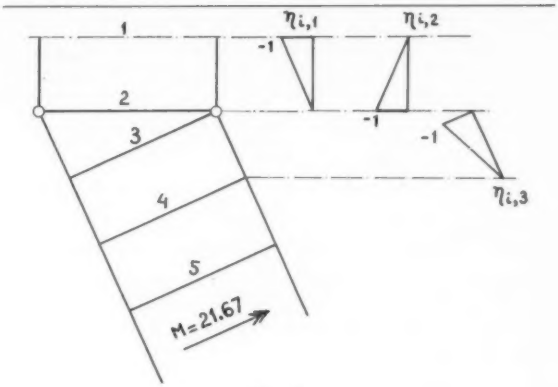

FIG. 1.

It should be noted that, generally

$$\eta_{ik} \neq \eta_{ki}$$

in contrast to the analogous but not identical *dimensional* quantities γ from Eq. (9) in the work of Best.[2]

An example may clarify the procedure. A swept wing with a constant cross section over the whole span, under a constant pure bending moment of 21.67 in the outer wing, is considered.

From the formal indeterminate analysis, applied as given in reference 4, the moments found in the rear spar are:

Station	1	2	3	4
Rear spar	12.05	13.00	12.71	11.57

As the moments of inertia and the heights of front and rear spar were assumed equal, the ultimate bending moment is determined by the moment in the rear spar at station 2. To improve the efficiency of the structure, the cross-sectional area of the rear spar in the root region is modified in the following way:

Between station 1 and 2: $\lambda = A_0/A_m = 0.9$

In the bay between station 3 and 4, λ increases from 0.9 at station 3 to 1.0 at station 4.

The η_{ik} values as defined before are (compare Fig. 1):

$i\,k \rightarrow$ $\downarrow$	1	2	3	
1	0.0943	0.0846	0.0545	
2	0.0742	0.0735	0.0575	
3	0.0644	0.0653	0.0626	
..	....	....	....	
4	0.0378	0.0390	0.0513	[needed in Eq. (7)]

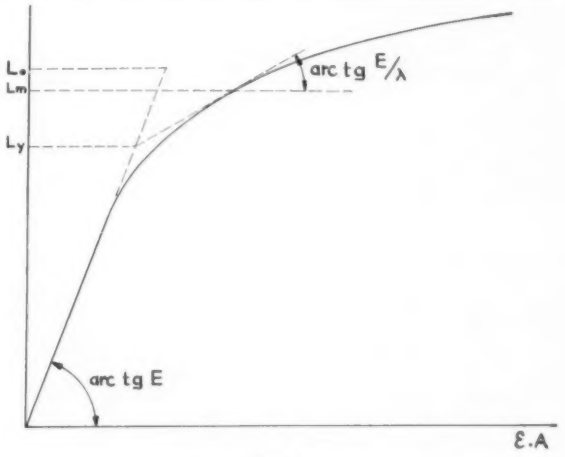

FIG. 2.

Hence, from Eq. (6), with $1 - \lambda = 0.1$,

$$+0.99057L_{m_1} - 0.00846L_{m_2} - 0.00545L_{m_3} = 12.05$$
$$-0.00742L_{m_1} + 0.99265L_{m_2} - 0.00575L_{m_3} = 13.00$$
$$-0.00644L_{m_1} - 0.00653L_{m_2} + 0.99374L_{m_3} = 12.71$$

Solving these equations,

$$L_{m_1} = 12.37, \quad L_{m_2} = 13.26, \quad L_{m_3} = 12.95$$

From Eq. (7) the altered moment at station 4 is computed

$$L_{m_4} = 11.57 + (0.1 \times 0.0378 \times 12.37) + (0.1 \times 0.0390 \times 13.26) + (0.1 \times 0.0513 \times 12.95) = 11.73$$

With $\lambda = 0.9$, the maximum stress in the rear spar is then reduced from $13.00h/J$ to $0.9\,(13.26h/J) = 11.92\,h/J$.

If $\lambda < 2$, a fairly good approximation of the value of L_{m_i} is given by

$$L_{m_i} = \frac{L_{0_i}}{1 - \sum_k \eta_{ik}(1 - \lambda_k)\,(L_{0_k}/L_{0_{ii}})} \qquad (8)$$

where the solution of the simultaneous linear equations is avoided.

The same principle can be applied to a variation of Young's modulus in a redundant structure.[5]

Eq. (6) then reads:

$$(L_{m_i} - L_{y_i}) - \sum_k \eta_{k_i}\,(1 - \lambda_k)\,(L_{m_k} - L_{y_k}) = (L_{0_i} - L_{y_i}) \qquad (9)$$

With a linearized stress strain curve Eq. (9) yields a straightforward solution.

In the general case of a nonlinear stress-strain curve, it leads to a rapidly converging iteration procedure.

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On the Variation of Heat Transfer with Mach Number in Wind Tunnels Having Constant Supply Conditions

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December 22, 1952

In recent measurements of the heat transmission on cones at Mach Numbers, M, from 0.88 to 4.65, Eber[1] found that the experimental data could be well represented by the incompressible laminar-flow solution for supersonic flow over a cone

$$Nu = 0.767R^{0.5}Pr^{0.33} \qquad (1)$$

where Nu is the average Nusselt Number, R is the Reynolds Number, and Pr is the Prandtl Number. However, laminar-flow analyses that include the effects of compressibility (e.g., reference 2) predict effects of M_1, T_w/T_1, and T_1 upon heat transfer, where T is the static temperature and 1 and w refer to conditions at the outer edge of the boundary layer and at the wall, respectively.

In reference 2, several charts of $C_{f_1}\sqrt{R_1}$ vs. M_1 for constant values of T_w/T_1 are given for $Pr = 0.725$ for several values of θ, where C_f is the average skin-friction coefficient, θ equals T_c/T_1, and T_c is the constant in the Sutherland viscosity equation. In the range $0 < M_1 < 5$, $^1/_4 < T_w/T_1 < 4$, and $^1/_3 < \theta < 3$ covered by the measurements in reference 1, these charts show that $C_{f_1}\sqrt{R_1}$ could vary from 1.1 to 1.4. It is also shown that the incompressible relation between friction and heat transfer holds for compressible flow, so that

$$Nu_1/\sqrt{R_1} = C_{f_1}\sqrt{R_1}\,Pr^{0.33}/2 \qquad (2)$$

if Nu_1 is defined using the temperature difference $T_e - T_w$, where T_e is the equilibrium temperature. Applying the boundary-layer transformation from the flat plate to a cone in supersonic flow and assuming $Pr = 0.725$ gives

$$\left(\frac{Nu_1}{\sqrt{R_1}}\right)_{\text{cone}} = \frac{2\sqrt{3}}{3}\,\frac{(0.725)^{0.33}}{2}\,(C_{f_1}\sqrt{R_1})_{\text{flat plate}} = 0.515(C_{f_1}\sqrt{R_1})_{\text{flat plate}} \qquad (2a)$$

Consequently, for the range of variables given above the possible variation of $Nu_1/\sqrt{R_1}$ is from 0.56 to 0.73.

However, for wind tunnels such as the one used in reference 1 having atmospheric supply temperature T_0, there is a definite relationship between θ and M_1 (since the stagnation temperature equals T_0 and is constant across any shock waves formed by the model) given by

$$\theta = \frac{110}{T_0}\,\frac{T_0}{T_1} = \frac{110}{T_0}\left(1 + \frac{\gamma - 1}{2}\,M_1^2\right) \qquad (3)$$

where T_c has been taken as 110°K. Using Eq. (3) and particular values of T_0 and γ, one can compute theoretical curves of $Nu_1 \div \sqrt{R_1}$ vs. M_1 for constant values of T_w/T_1. In addition, assuming $T_w = T_e$ (which is not far from correct for the data of reference 1) and a recovery factor $r = \sqrt{Pr} = 0.85$ gives

$$\frac{T_w}{T_1} = 0.15 + 0.85\left(1 + \frac{\gamma - 1}{2}\,M_1^2\right) \qquad (4)$$

and this equation, in conjunction with Eq. (3), determines a unique curve of $Nu_1/\sqrt{R_1}$ vs. M_1. The curves of $Nu_1/\sqrt{R_1}$ for constant T_w/T_1 and for T_w/T_1 given by Eq. (4) are shown in Fig. 1, together with the constant value from Eq. (1) for incompressible flow. The curves were computed for $T_0 = 294$°K. and $\gamma = 1.4$, which are appropriate values for the data of reference 1. Since the calculations show that in this particular case—i.e., for constant T_0—compressible flow theory also predicts an almost constant value of $Nu_1/\sqrt{R_1}$ for $0 < M < 5$, it would be unwise to conclude from the experimental data that the incompressible relation given by Eq. (1) also holds for other cases, such as free flight, where T_0 varies with M.

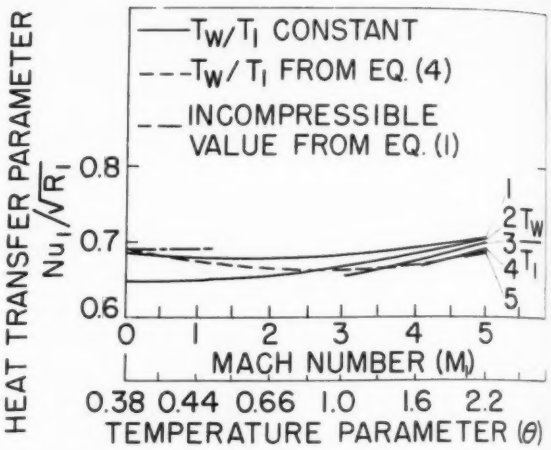

Fig. 1. Variation of heat-transfer parameter $Nu_1/\sqrt{R_1}$ with Mach Number for constant supply temperature. $T_0 = 294$°K., $Pr = 0.725$.

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Some Experiments on the Effect of a Single Roughness Element on Boundary-Layer Transition

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July 20, 1952

SEVERAL YEARS AGO we published a paper[1] on the permissible roughness to boundary-layer transition, which is referred to by Loftin[2] in connection with his measurement and also by Schlichting in his new book on boundary layers.[3] Our previous idea, based on Schiller's hypothesis,[4] was that kv^*/ν must be constant when transition occurs at a single roughness element, where k is the height of roughness element, v^* the friction velocity, and ν the kinematic viscosity. This constant was determined by experiment on transition due to a wire stretched transversely over a flat plate (aluminum, 80 cm. long, 60 cm. wide, and 3 mm. thick), using a small total-pressure tube in contact with the plate at a fixed point (70 cm. behind the leading edge) for detecting transition. The constant thus determined was 13.

We found out later, however, by more careful measurement that transition does not always take place right behind a single roughness but that the boundary layer usually maintains laminar for a certain distance. This fact is also confirmed by Liepmann and Fila.[5] Since our research was published as the Wartime Report in Japan and has been known only within a limited circle, it seems to be worth while to recapitulate its major results.

The experiments being described in the present report were also conducted on a flat plate, 2.4 m. long, 2 m. wide, and 3 cm. thick, with leading and trailing edges chamferred, which was held vertically in a wind tunnel of relatively low turbulence. Transition velocity was determined by the total-pressure tube placed in contact with the plate at several points behind the wire, instead of at a fixed position as in the previous experiment. A typical result is shown in Fig. 1, in which the abscissa and ordinate are transition position (location of total-pressure tube) and transition velocity (mean wind-tunnel velocity when total pressure increases suddenly), respectively. The position of the roughness element is indicated by vertical broken line. A summary of all experiments is given in Fig. 2. These results show that the boundary layer maintains laminar for a certain distance behind a roughness element.

If we plot the values of transition velocity against the ratio x/x_0, we find that they are approximately independent of the location of roughness element, x_0, as shown in Fig. 3, x being the transition position. We were not much successful, however, in getting a single parameter that governs transition satisfactorily.

A parameter suggested by Fage and Preston[6] on ordinary transition, which is deduced from Taylor's hypothesis[7] of transition due to incipient separation, is

$$\xi_M = \frac{\theta u_T}{\nu}\left(\frac{\theta}{M}\right)^{1/5}\left(\frac{\nu}{\theta V}\right)^{2/5}$$

where θ is the momentum thickness, M is the mesh length of

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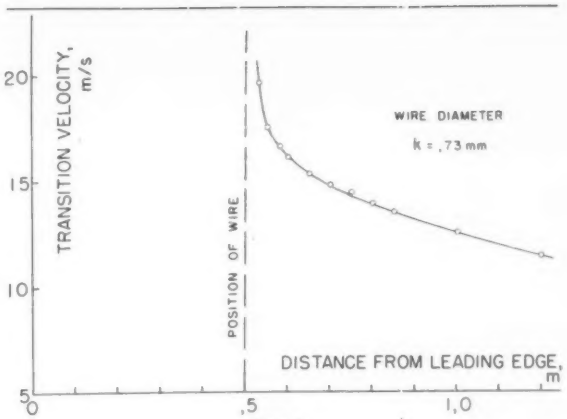

FIG. 1.

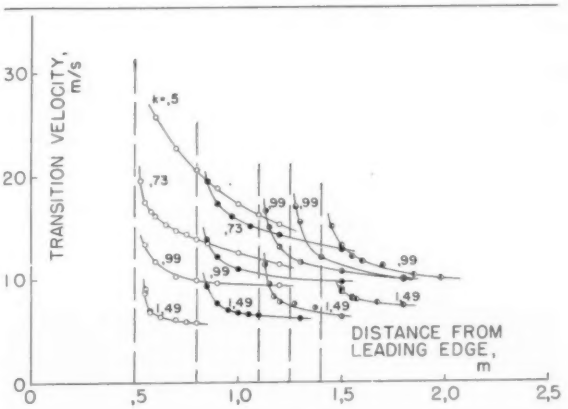

FIG. 2.

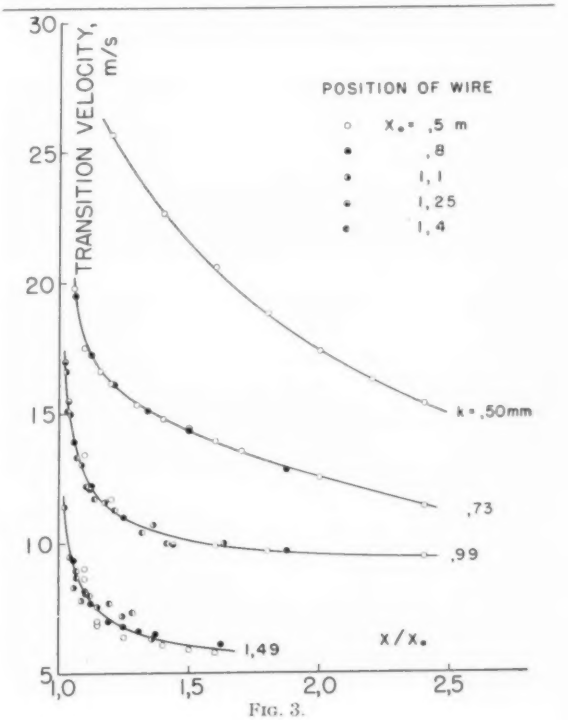

FIG. 3.

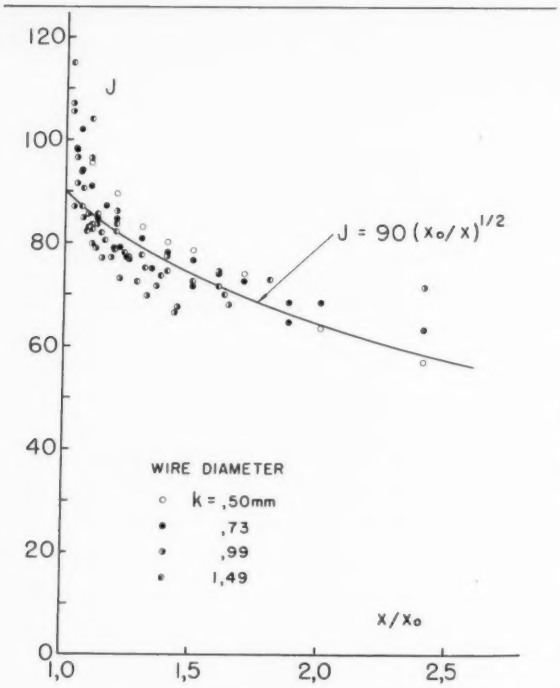

FIG. 4.

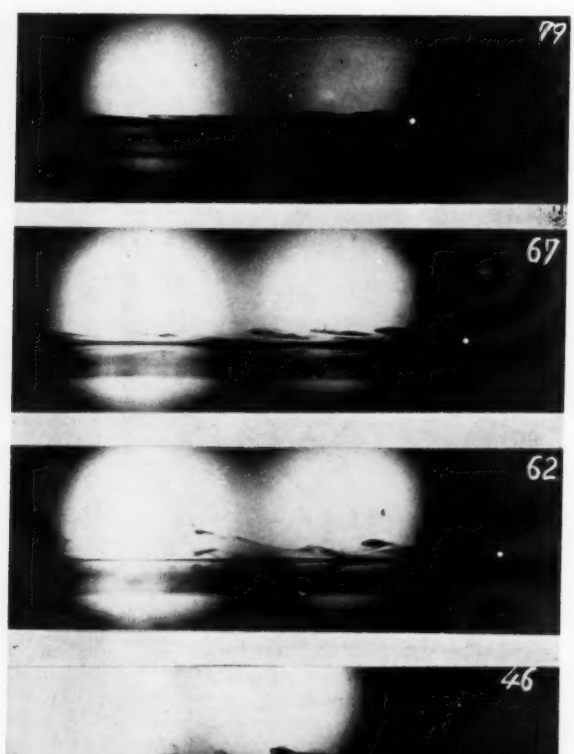

FIG. 5.

turbulence-producing grid, and u_T is the maximum turbulence velocity. ξ_M is supposed to be constant at transition point.

Now, if we assume that a similar parameter might exist for transition due to a roughness element by taking k and $u_k = 0.0576(k/x_0)\,(Vx_0/\nu)^{3/4}$ (velocity at the top of the roughness element) for M and u_T in the expression of ξ_M, respectively, the condition ξ_M = constant is replaced by

$$\frac{k}{x_0}\left(\frac{Vx_0}{\nu}\right)^{7/8}\left(\frac{x}{x_0}\right)^{1/2} = \text{const.}$$

or

$$J = \text{const.}\ (x_0/x)^{1/2}$$

where

$$J \equiv (k/x_0)\,(Vx_0/\nu)^{7/8}$$

Such a parameter J is plotted against x/x_0 in Fig. 4. We may take 90 as a constant numerical factor. Although the scattering is appreciable, it seems to give somewhat of a feature of transition due to single roughness element. We also tried our previous proposal, which reads

$$K \equiv kv^*/\nu = \text{const.}$$

or

$$(k/x_0)\,(Vx_0/\nu)^{3/4} = \text{const.}$$

but it has much more scattering of points than the case of J.

On the other hand, flow pattern was observed in a water tank with a view to studying the mechanism of transition. A flat plate (plastic, 60 cm. long, 40 cm. wide, and 1 cm. thick with rounded leading edge) was submerged in water horizontally, and a pipe of 4-mm. diameter was attached to the plate transversely, 20 cm. behind the leading edge, as a roughness element. The flat plate was towed by carriage. Dye (red ink diluted with water) was injected through a small hole on top of the pipe at the centerline of the plate. Some pictures taken through glass side windows of the water tank are shown in Fig. 5. The horizontal shadow is the flat plate. A white dot at the right corner shows the position of the pipe. At first, small vortices come out from the top of the pipe with constant pitch. Then, neighboring two or consecutive vortices catch up each other and produce a larger vortex. The larger vortices thus produced roll over the flat plate steadily, increasing distance between vortices gradually. At some point, these vortices suddenly explode and diffuse into the general flow and dissolve themselves to random motion with smaller vorticity. This might be transition. Furthermore, we should mention that this burst of flow pattern never occurs in between vortices, so that it may have some correlation with the intermittent character of turbulent boundary layer.

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On the Recovery Factor for Hypersonic Flow with a Self-Induced Pressure Gradient†

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January 19, 1953

Symbols

Physical quantities are denoted by an asterisk, whereas the corresponding nondimensional quantities are unstarred. The subscript ∞ denotes values in the undisturbed free stream far from the body, and the subscript δ denotes values at the edge of the boundary layer. The undisturbed free-stream values at infinity are the characteristic measures for all nondimensional quantities. The characteristic length measure is L^* (e.g., the length of the body).

- x^*, y^* = coordinates parallel and normal to surface, respectively, with origin at leading edge of plate
- u^*, v^* = components of velocity parallel and normal to surface, respectively
- p^* = pressure
- ρ^* = density
- T^* = absolute temperature
- μ^* = viscosity
- ν^* = kinematic viscosity, μ^*/ρ^*
- γ = ratio of specific heats, c_p/c_v
- M_∞ = free-stream Mach Number
- Re_{x^*} = Reynolds Number based on free-stream quantities and distance from leading edge
- Pr = Prandtl Number
- C = constant in linear viscosity-temperature relation $\mu = CT$
- $\chi = \sqrt{C}M_\infty^3/\sqrt{Re_{x^*}} = \sqrt{C}\bar{\chi}$
- $\eta = y^*\sqrt{u_\infty^*/\nu_\infty^* x^* C}$
- $\zeta = \psi^*/\sqrt{u_\infty^* \nu_\infty^* L^* C}$, where ψ^* is the stream function
- λ_1 = function of ζ defined by Eq. (13)

Discussion

In references 1 and 2, it is shown that as a result of the curvature of the relatively thick boundary layer in the hypersonic laminar flow over a flat plate (or wedge), a sufficiently large outward streamline deflection is induced to bring about an important change in the "effective" geometric shape of the body, with the result that pressure variations are propagated into the main stream along Mach lines. This external pressure field in turn feeds back into the boundary layer and affects its rate of growth. For such an interaction problem the Prandtl boundary-layer equations are proved valid. It is further shown that the significant hypersonic viscous flow parameter, which is a measure of the magnitude of the pressure variations produced in the external flow by the viscous layer, is $M_\infty^3/\sqrt{Re_{x^*}} = \chi$, or the product of the free-stream Mach Number, M_∞, and the streamline inclination induced by the zero pressure gradient, flat-plate boundary-layer flow.

When the hypersonic parameter, χ, is less than, or equal to, 2 or 3 (say), then it is a good approximation to consider the external flow as an isentropic Prandtl-Meyer flow.‡ In this weak interaction or back end region, asymptotic solutions for the flow quantities may be obtained by working upstream from a location far downstream of the leading edge.

The analytic formulation of the problem starts with the Prandtl-Meyer relation, which for $M_\infty >> 1$ may be integrated to give for the ratio of local to free-stream pressure

$$p = \left(1 + \frac{\gamma - 1}{2} M_\infty v_\delta\right)^{2\gamma/(\gamma-1)} \tag{1}$$

where the vertical velocity component at the edge of the viscous layer is

$$v_\delta = K\sqrt{C}\, M_\infty^3/\sqrt{Re_{x^*}} = K\bar{\chi}/M_\infty$$

and where K is a constant of the order of $1/4$ given by the usual zero pressure gradient, flat-plate solution. The constant C arises from the linear viscosity-temperature relation $\mu = CT$.** If Eq. (1) is expanded the pressure is given by

$$p = 1 + \gamma K\bar{\chi} + \gamma\frac{(\gamma+1)}{4} K^2\bar{\chi}^2 + \ldots \tag{2}$$

while from the Bernoulli equation and the isentropic relation the external velocity and temperature fields are expressed as

$$u_\delta = 1 - \left(\frac{K}{M_\infty^2}\right)\bar{\chi} - \frac{(\gamma-1)}{4}\left(\frac{K^2}{M_\infty^2}\right)\bar{\chi}^2 + \ldots \tag{3}$$

$$T_\delta = 1 + (\gamma-1)K\bar{\chi} + \frac{(\gamma-1)^2}{4} K^2\bar{\chi}^2 + \ldots \tag{4}$$

Solutions of the boundary-layer equations are then sought in the form of asymptotic series of the type

$$u(x, y) = u_0(\zeta) + u_1(\zeta)\bar{\chi} + \ldots \tag{5}$$

$$T(x, y) = T_0(\zeta) + T_1(\zeta)\bar{\chi} + \ldots \tag{6}$$

where $u_0(\zeta)$, $u_1(\zeta)$, etc., each satisfies an ordinary second-order differential equation (u_0 and T_0 represent the zero pressure gradient, flat-plate solution), and where ζ is the stream-function parameter proportional to $y/\sqrt{x}$.

In the coordinates x, ζ the x-momentum equation is

$$xuu_x - \frac{\zeta}{2}uu_\zeta = pu(uu_\zeta)_\zeta - \frac{x}{\gamma M_\infty^2}\frac{p_x}{p}T \tag{7}$$

and the energy equation is

$$xT_x - \frac{\zeta}{2}T_\zeta = \left(\frac{\gamma-1}{\gamma}\right)\frac{xp_x}{p}T + \frac{p}{Pr}(uT_\zeta)_\zeta + (\gamma-1)M_\infty^2 pu(u_\zeta)^2 \tag{8}$$

Here $\zeta = \psi^*/\sqrt{\nu_\infty^* u_\infty^* x^* C}$, while $\rho u^* = \partial\psi^*/\partial y^*$ and $\rho v^* = -\partial\psi^*/\partial x^*$. By employing Eq. (2) for the pressure, the x-momentum and energy equations are reduced to the following forms for u_0 and T_0

$$-(\zeta/2)u_0' = (u_0u_0')' \tag{9}$$

$$\frac{\zeta}{2}T_0' + \frac{(u_0T_0')'}{Pr} = -(\gamma-1)M_\infty^2 u_0(u_0')^2 \tag{10}$$

while for the first approximation

$$u_1'' + \frac{(4u_0' + \zeta)}{2u_0}u_1' + \frac{(2u_0'' + 1)}{2u_0}u_1 = -\frac{K}{2u_0^2M_\infty^2}(T_0 - \gamma M_\infty^2\zeta u_0u_0') \tag{11}$$

$$\lambda_1'' + \left(\frac{u_0'}{u_0} + \frac{\zeta Pr}{2u_0}\right)\lambda_1' + \frac{Pr}{2u_0}\lambda_1 = \frac{K}{2M_\infty^2u_0}\frac{d}{d\zeta}\times\left(-2KM_\infty^2 + \int\frac{T_0}{u_0}d\zeta\right)\left[(\gamma-1)M_\infty^2Pru_0 + \frac{T_0'}{u_0'}\right] \tag{12}$$

where

$$T_1 = (T_0'u_1/u_0') + \lambda_1 \tag{13}$$

As pointed out to the authors by Maslen, the homogeneous solution of Eqs. (11) and (12) may be given in closed form. The general integrals of the above equations may therefore also be obtained in closed form. Since the present paper is concerned with the recovery factor or equilibrium temperature, only the solution of Eq. (12) will be given. By use of the relation

† This work was supported by the U.S.A.F., Air Research and Development Command, under Contract No. AF-33 (038)-250.

‡ A comprehensive discussion of this point will be presented in a forthcoming paper.

** Although the present analysis is carried out for a linear viscosity-temperature relation and Prandtl Number constant, Maslen[2] has shown the calculation can be generalized to the case where μ and Pr are arbitrary functions of the temperature.

$$\frac{u}{T} = \frac{d\zeta}{d\eta} \text{ where } \eta = y^* \sqrt{\frac{u_\infty^*}{\nu_\infty^* x^* C}} \tag{14}$$

the integral of Eq. (12) may be written in terms of the normal distance parameter as

$$\lambda_1(\eta) = (T_0 u_0')^{Pr} \left\{ A + B \int_0^\eta \frac{d\eta}{(T_0 u_0')^{Pr} T_0} + \frac{K}{2M_\infty^2} \int_0^\eta \times \right.$$
$$\left. \frac{(-2KM_\infty^2 + \eta)}{(T_0 u_0')^{Pr} T_0} \left[(\gamma - 1) M_\infty^2 Pr u_0 + \frac{T_0'}{u_0'} \right] d\eta \right\} \tag{15}$$

where A and B are the constants of integration.

The boundary conditions on the velocity to match the external conditions [Eq. (3)] are

$$u_0(\infty) = 1, \qquad u_1(\infty) = -K/M_\infty^2 \tag{16}$$

while from the condition of zero slip at the wall

$$u_0(0) = 0, \qquad u_1(0) = 0 \tag{17}$$

On the other hand from Eq. (4) the requirements on the temperature are that

$$T_0(\infty) = 1, \qquad T_1(\infty) = (\gamma - 1)K \tag{18}$$

At the wall if the temperature is specified then

$$T_0(0) = T_w, \qquad T_1(0) = \lambda_1(0) = 0 \tag{19}$$

while if the surface is insulated then

$$T_0'(0) = 0, \qquad T_1'(0) = \lambda_1'(0) = 0 \tag{20}$$

For the case of constant wall temperature with heat transfer, it is evident that the constant A in Eq. (15) must be zero. In reference 3, however, it was found that the last integral on the right-hand side of Eq. (15) satisfied all the boundary conditions automatically and therefore B cannot be determined from the above boundary conditions alone. In order to determine B, Maslen found it was necessary to add the conditions that the momentum and displacement thickness be finite, from which B could be shown to vanish. However, Crocco and Lees pointed out in an unpublished note that the term in Eq. (15) involving B behaves like $1/\eta$ far from the surface and that such a term represents a solution of the Euler equation appropriate to the inviscid external flow, for which the viscous terms are negligible compared to the inertia terms. It can therefore be discarded immediately as inappropriate for the boundary-layer problem. A similar argument can be used for determining the proper solution in Falkner and Skan's treatment of the incompressible boundary layer with pressure gradient. This argument replaces the original somewhat unsatisfactory stipulation that the solution that approaches the boundary condition at infinity most rapidly must be selected.

In the insulated case since $\lambda_1'(0) = 0$, B must be zero while A is not determined by the boundary condition at the wall. From the zeroth order solutions it is known that $A(T_0 u_0')^{Pr}$ goes like $Ae^{-bPr\eta^2}$ for large η. The constant A thus at first appears to be indeterminate. However, by a continuity argument A can again be shown to be zero.

Consider the case of constant wall temperature, where $A = 0$. With the free-stream Mach Number and Prandtl Number fixed, select a value of η somewhere in the boundary layer and for this normal distance plot the temperature ratio T versus T_w, where the values of T_w are both greater and less than, but not equal to, the equilibrium wall temperature in the insulated case. Since the solution must be analytic in T_w then for values of T differing from $T_{equil.}$ by an infinitesimal amount $\Delta T_w = \epsilon$, the solution is continuous and defined. At the point $T_w = T_{equil.}$ if we make $|A| > 0$ by a finite amount larger than ϵ, then T is discontinuous. It is known *a priori* however, that the solution cannot be discontinuous and therefore the only alternative is that $A = 0$.

By referring to Eq. (15) one sees that $\lambda_1(0) = 0$, and therefore *the equilibrium wall temperature has exactly the same value as for zero pressure gradient.* Thus Busemann's conclusion that the recovery temperature is unaffected by pressure gradient for $Pr = 1$ is here generalized to arbitrary Pr, at least for the case of weak interaction in hypersonic flow where Eqs. (3) and (4) hold. This same argument can be extended to all orders of χ, so long as the asymptotic expansions [Eqs. (3) and (4)] hold.

Tifford and Chu's numerical results[4] for the Falkner-Skan case for a compressible laminar boundary layer indicate that the calculated effect of pressure gradient on recovery factor is zero within the numerical errors of the calculation, as shown by examining their results for $Pr = 1$. This suggests that our conclusion that pressure gradient has no effect on recovery factor for any Pr may also hold for the Falkner-Skan type of distribution.

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Matrix Methods for Redundant Structures

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December 5, 1952

FOR MANY YEARS, G. Kron has used matrix methods to establish systems of equations of electrical, and also dynamic, structures. More recently, Kron's methods were modified to be used also for elastic structures.[1] Simultaneously, the classical methods used by Ebner and Köller, and later on by Levy, were given a new form, more suited to routine computation.[2] It turned out that both methods of reasoning led to the same matrix relations. However, even if the computational principles are the same in both cases, it is not certain that the different methods of reasoning will, in all actual problems, lead to the same detailed schemes of computation. It may be that the more general concepts used by Kron will, in practical cases, lead to more practical schemes. Therefore it might be worth while for structural engineers to study some of Kron's papers, referred to in reference 1 for instance.

Recently, a new paper on the subject was published in the JOURNAL OF THE AERONAUTICAL SCIENCES. It is encouraging to see that this new technique is coming more and more into use, and it is to be hoped that this well-written paper will give still more stimulation in that direction.

Some remarks in connection with reference 3 might be of interest.

The authors state: "One of the large labor items is the solving of the equations . . . ." Of course, this statement is true, but it might strengthen the already too general misconception that solving the equations is the dominant problem. In reality, *the establishment* of the equations is the predominant labor-consumer. Also it is just this labor that is made more rational by the use of matrices. In reference 1 and in references 10 and 14 of that paper, it was shown that plausible approximations could be used to define transformations by which the systems of equations were reduced. These same methods may also be used for reducing the work of establishing the equations.

Of great practical interest is a further development of the matrix methods, demonstrated in the Saab Technical Note T.N. 3,

referred to in reference 1. There it is shown how the matrices for a complete "beamlike" structure, a wing for instance, may be easily obtained from matrices established for single cells, such as that of Fig. 6 in reference 3. As a result, it is possible by using this scheme and giving formulas for the two typical matrices for a single cell, rather than for single components, to put down everything that is necessary to perform a complete calculation.

In that way it would be possible, for example using an IBM Card-Programmed Calculator, to perform all computations in automatic machinery, once the overall dimensions and the material distribution are given. It is believed that trivial generalization of the "cell-formulas" given in Saab T.N. 3 would make possible wholly automatic computations of complete beamlike structures such as wings and fuselages.

The statement in reference 3, that for the establishment of the matrices D, which represent the determinate load distribution, mere slide-rule accuracy should be necessary, deserves some discussion. Surely, by taking extra precision in the machine calculation, as the authors suggest, rounding-off errors may be avoided. However, the inversion of the matrix α_{rs} may lead to the loss of one or more significant figures, depending on how ill-conditioned the matrix is. With the usual choice of redundants and the one used in reference 3, the matrix α_{rs} will, in general, be well-conditioned so that for large systems of equations the loss of about one significant figure only will be probable. Then, however, starting with slide-rule accuracy only, we will obtain the stress distribution with two-digit precision only. This is true if no rounding-off errors occur. Still more serious will be the fact that the flexibility matrix for the structures, A_{mn}, will also have only about two-digit precision. This matrix, however, is, in general, rather ill-conditioned. If, for instance, this matrix is to be used for vibration or flutter calculation, the highest eigenvalue will be obtained to about two digits, but an eigenvalue that differs from the highest one by a factor of 10^{-1} will have only one significant digit. Hence the writer believes that five digits or more should be used for establishing D. The machine computations should then be performed with at least seven digits in order that a final answer shall be obtained which is of slide-rule precision.

It is to be observed that, whereas the extra figures used in the machine calculations may be obtained by simply adding zeros to the right, the significant figures of the elements in the γ matrix must be obtained from the exact internal geometric relations for the structure, when the main dimensions are defined to the same precision by adding right-hand zeros.

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Systematic Analysis of Redundant Elastic Structures by Means of Matrix Calculus

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December 15, 1952

RECENTLY, LANGEFORS[1] HAS GIVEN some aspects of matrix transformation applied to analysis of redundant elastic structures. This corresponds to Kron's method[2] for electrical networks. As Kron's presentation of his method does not seem to be very rigorous—i.e., see reference 3, pp. 347–348—the statement is useful that *analysis of all linear problems* can be presented by matrix transformation. There is no need to start from a "certain" matrix method to develop "another" matrix method for another case.

In the case of analysis of elastic redundant structures this statement was proved in two papers[4, 5] by the writer. These papers were also reviewed in different abstracts—i.e., Applied Mechanics Review, Vol. 4, No. 4, April, 1951.

Comparing Langefors' principal equations with equations in the writer's papers we will find, therefore, analogous expressions given here always pairwise one under the other with their different notations (numbers opposite equations mean original numbering and reference, respectively),

Energy (*Langefors' paper*): $2U = P'VP$ (4)[1]

Energy (*writer's papers*): $\delta_{ik} = S\left(\sqrt{\frac{1}{\rho}}\, I \sqrt{\frac{1}{\rho}}\right) S$ (15)[4]

(The different signs ($'$) and ($^-$) both indicate the transposed matrix.)

The P's are all forces acting on all hypothetical cuts separating structural elements, V is a matrix that introduces the elastic behavior of the structure, the S's are all statical parameters necessary to determine any internal and/or external load system,

$$\sqrt{1/\rho}\cdot I \cdot \sqrt{1/\rho} = R \qquad (22)^4$$

is a matrix that introduces the elastic behavior of the structure by means of Barrois' integration matrix I. Matrix R was called "Rigidities Matrix" in references 4 and 5, but it is better to call it "Deformability Matrix."

The energy expressions δ_{ik} are established for a set of force systems; they present a generalized matrix of bilinear forms. The factor 2 is omitted in this matrix of "mixed work expressions" (bilinear forms) because it does not appear in expressions of energy established for virtual displacements or virtual forces considered here.

Partial differential quotients of energy expression give the system of linear equations for the X's,

$$\partial U/\partial X = V_x X + C'VDQ = 0 \qquad (7)^1$$

with

$$V_x = C'VC \qquad (8)^1$$

After formal inversion of V_x,

$$X = -V_x^{-1}(C'VD)Q$$

Writer's notations:

$$\partial U/\partial x_u = 0$$

$$x_u = -\delta_{uv}^{-1}\cdot\delta_{kv}F_k \qquad (18a)^4$$

Matrices C and D describe equilibrium statics for each structural element. Here we have identities, not only $V_x^{-1}(C'VD) \equiv \delta_{uv}^{-1}\delta_{kv}$ but also $V_x \equiv \delta_{uv}$ and $(C'VD) \equiv \delta_{kv}$.

Indeed, considering Langefors' reference (10)[6] or his numerical example, one will find some V-matrices established for structural elements like prismatical stringers, plates, etc.—i.e.,

$$V = \begin{bmatrix} 2r & r \\ r & 2r \end{bmatrix}$$

with

$$r = l/6EA$$

where l = length of beam element and EA = rigidity and in writer's papers:

$$R = \sqrt{\frac{1}{\rho}}\cdot I \cdot \sqrt{\frac{1}{\rho}} \qquad (22)^4$$

with—i.e.,

$$I = \frac{1}{6}\begin{bmatrix} 2\Delta s & \Delta s \\ \Delta s & 2\Delta s \end{bmatrix}$$

(see chapt. VI of reference 4) where Δs = interval length and ρ = rigidity.

Also, matrices C, D[1] and F_{0k}, F_u[4], respectively, are found to be identical.

We compare the global matrices of influence submatrices:

$$\begin{bmatrix} C'VC & C'VD \\ D'VC & D'VD \end{bmatrix} \qquad (4d)^1$$

$$D = \left[\begin{array}{c:c} \delta_{ik}^* & \delta_{iv} \\ \hdashline \delta_{uk} & \delta_{uv} \end{array}\right]; \quad \delta_{iv} = \bar{\delta}_{uk} \qquad (25)^4$$

where D is calculated by

$$\left[\begin{array}{c} \bar{F}_{0kp} \\ \hdashline \bar{F}_{up} \end{array}\right] \quad R \quad \left[\begin{array}{c:c} F_{0kp} & F_{up} \end{array}\right] = D \qquad (26)^4$$

Hence, the identities

$$C'VC \equiv \delta_{uv} = \bar{F}_u R F_u$$
$$D'VD \equiv \delta_{ik}^* = \bar{F}_{0k} R F_{0k}$$
$$C'VD \equiv \delta_{uk} = \bar{F}_u R F_{0k}$$

hence,

$$C \equiv F_u \text{ and } D \equiv F_{0k}$$

Development of Langefors' deformation matrix Z

$$Z = V_q - V_{xq}' V_x^{-1} V_{xq} \qquad (13)^1$$

also was given by the writer:

$$\delta_{ik} = \delta_{ik}^* - \delta_{iv}\delta_{uv}^{-1}\bar{\delta}_{iv} \qquad (24)^4$$

with

$$\delta_{iv} = \bar{\delta}_{uk} \qquad (25)^4$$

The "Solution by Parts" is a matrix procedure in connection with the well-known Method of the Statical Indeterminate Sub-Systems. The writer dealt with procedure in his second paper.[5] There is only a small difference in the number of subdivisions; Langefors introduces three parts, and present author two, but this does not modify the principle.

$$\begin{bmatrix} V_x & V_{xp} & \\ V_{xp} & V_p & V_{yp} \\ & V_{yp} & V_y \end{bmatrix}\begin{bmatrix} X \\ p \\ Y \end{bmatrix} = \begin{bmatrix} -F_xQ \\ -F_pQ \\ F_yQ \end{bmatrix} \qquad (15)^1$$

$$\left[\begin{array}{c:c} D_{fg} & D_{fl} \\ \hdashline D_{ig} & D_{il} \end{array}\right]\left[\begin{array}{c} X_{gk} \\ \hdashline X_{lk} \end{array}\right] + \left[\begin{array}{c} D_{fk} \\ \hdashline D_{ik} \end{array}\right] = 0 \qquad (4)^5$$

There is an error in Eq. (15)[1] because it must be that $V = V'$ (global V_{xpy}-matrix) but $V_{xp} \neq V_{xp}'$ and $V_{yp} \neq V_{yp}'$ in the general case. Therefore we have the modified Eqs. (16) and (17):[1]

$$\left.\begin{aligned} V_xX &= -V_{xp}p - F_xQ \\ V_yY &= -V_{yp}'p - F_yQ \end{aligned}\right\} \qquad (16)^1$$

(not established *in extenso* in reference 5) and

$$\left.\begin{aligned} X &= -V_x^{-1}V_{xp}\cdot p - V_x^{-1}F_xQ \\ Y &= -V_y^{-1}V_{yp}'p - V_y^{-1}F_yQ \end{aligned}\right\} \qquad (17)^1$$

$$\left[\begin{array}{c} X_{gk} \\ \hdashline X_{lk} \end{array}\right] = -\left[\begin{array}{c:c} D_{fg} & D_{fl} \\ \hdashline D_{ig} & D_{il} \end{array}\right]^{-1}\left[\begin{array}{c} D_{fk} \\ \hdashline D_{ik} \end{array}\right] \qquad (6)^5$$

The writer's Eqs. (4) and (6) do not express exactly the Langefors' problem. The redundants p are not introduced in the simplified presentation. But by extension of our relations we obviously can write

$$\left[\begin{array}{c:c:c} D_{fg} & D_{fl} & 0 \\ \hdashline D_{ig} & D_{il} & D_{iv} \\ \hdashline 0 & D_{ul} & D_{uv} \end{array}\right]\left[\begin{array}{c} X_{gk} \\ \hdashline X_{lk} \\ \hdashline X_{vk} \end{array}\right] + \left[\begin{array}{c} D_{fk} \\ \hdashline D_{ik} \\ \hdashline D_u \end{array}\right] = 0 \qquad (4)^5$$

The formal matrix inversions introduced here can, of course, be substituted by any elimination procedure for systems of linear equations—i.e., by the Gauss-Banachiewicz method or "modernized" Gauss's algorithm (see reference 3, pp. 248–257)—which demands least writing work.

But there is yet another rather important fact in applying the matrix method for elastic redundant structures—namely, the use of superposition of equilibrium systems instead of isostatic internal force systems.[7] Use of equilibrium systems will avoid all assumptions for any hypothetical cuts and the redundants X are no longer forces, etc., but superposition coefficients determined by principle of least work. One final internal and/or external force system of an elastic structure of redundancy V is then a superposition of $1 + V$ equilibrium systems, and we choose in the practical case one arbitrary equilibrium system that contains also the external loads and which may be chosen as an estimate of the final force system, and a set of V self-equilibrated systems of simplest composition. Then we write all parameters, defining these equilibrium systems, in $1 + V$ separated columns F, or $N + V$ columns if there are N external load systems. When this work is done and after having established also deformability matrix R, the matrix method will allow a least routine computing work that can be subdivided in different parts for different computers[8] to save time and to be well verified numerically.

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Errata—"On Heat Transfer over a Sweat-Cooled Surface in Laminar Compressible Flow with a Pressure Gradient"[1]

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January 16, 1952

In Eq. (23), page 709, the power of (T_1/T_∞) in the integrand should be $(J_2 + \gamma - 2)/(\gamma - 1)$ instead of $(J_2 + \gamma - 1)/(\gamma - 1)$. In addition, the word "velocity" on p. 712, second line of the second column, should be replaced by the words "mass flow."

In the upper portion of Fig. 2 on page 711, the labeling on the two curves should be interchanged—that is, the lower curve should be $h = 0$ and the upper curve should be $h = 1$.

Reference

[1] Morduchow, Morris, *Heat Transfer over a Sweat-Cooled Surface*, Journal of the Aeronautical Sciences, Vol. 19, No. 10, pp. 705–712, October, 1952.

Note on the Solution of the Unsteady Laminar Boundary-Layer Equations

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January 19, 1953

IN A RECENT PAPER, Moore[1] analyzes in detail the laminar boundary layer along an insulated semi-infinite flat plate moving with an arbitrary time-dependent velocity in compressible fluids. By using the following transformations of coordinates, stream function, and temperature

$$\left.\begin{aligned} Y &\equiv \int_0^y \frac{\rho}{\rho_\infty}\,dy, \quad X \equiv x, \quad T \equiv t \\ u &\equiv \frac{\rho_\infty}{\rho}\frac{\partial \psi}{\partial y} = \frac{\partial \psi}{\partial Y} \\ v &\equiv -\frac{\rho_\infty}{\rho}\left(\frac{\partial \psi}{\partial x} + \frac{\partial}{\partial t}\int^y \frac{\rho}{\rho_\infty}\,dy\right) = \\ &\qquad -\frac{\rho_\infty}{\rho}\left(\frac{\partial \psi}{\partial X} + \frac{\partial Y}{\partial X}\frac{\partial \psi}{\partial Y} + \frac{\partial Y}{\partial T}\right) \\ \psi &\equiv \sqrt{U\nu X}\, f(\sigma;\ \zeta_0, \zeta_1, \zeta_2, \ldots) \\ \frac{\theta}{\theta_\infty} &\equiv 1 + \frac{\gamma - 1}{2} M_\infty{}^2(T)\, r(\sigma;\ \zeta_0, \zeta_1, \zeta_2, \ldots) \\ \sigma &\equiv (Y/2)\sqrt{U/\nu X} \end{aligned}\right\} \quad (1)$$

the boundary-layer equations

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x}(\rho u) + \frac{\partial}{\partial y}(\rho v) = 0 \quad (2)$$

$$\rho\left(\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y}\right) = \rho\frac{dU(t)}{dt} + \frac{\partial}{\partial y}\left(\mu\frac{\partial u}{\partial y}\right) \quad (3)$$

$$\rho c_p\left(\frac{\partial \theta}{\partial t} + u\frac{\partial \theta}{\partial x} + v\frac{\partial \theta}{\partial y}\right) = \frac{\partial}{\partial y}\left(\lambda\frac{\partial \theta}{\partial y}\right) + \mu\left(\frac{\partial u}{\partial y}\right)^2 \quad (4)$$

are transformed into

$$\frac{\partial^3 f}{\partial \sigma^3} + f\frac{\partial^2 f}{\partial \sigma^2} = -8\zeta_0 + 2\left(2\zeta_0 + X\sum_{n=0}^{\infty}\frac{\partial^2 f}{\partial \sigma \partial \zeta_n}\frac{\partial \zeta_n}{\partial X}\right)\frac{\partial f}{\partial \sigma} - 2X\frac{\partial^2 f}{\partial \sigma^2}\sum_{n=0}^{\infty}\frac{\partial f}{\partial \zeta_n}\frac{\partial \zeta_n}{\partial X} + 4\frac{X}{U}\sum_{n=0}^{\infty}\frac{\partial^2 f}{\partial \sigma \partial \zeta_n}\frac{\partial \zeta_n}{\partial T} + 2\zeta_0\,\sigma\frac{\partial^2 f}{\partial \sigma^2} \quad (5)$$

and

$$\frac{\partial^2 r}{\partial \sigma^2} + Pr\, f\frac{\partial r}{\partial \sigma} + \frac{1}{2}Pr\left(\frac{\partial^2 f}{\partial \sigma^2}\right)^2 = 4\,Pr\left(2\zeta_0 r + \frac{1}{2}\zeta_0\,\sigma\frac{\partial r}{\partial \sigma} + \frac{X}{U}\sum_{n=0}^{\infty}\frac{\partial r}{\partial \zeta_n}\frac{\partial \zeta_n}{\partial T} + \frac{1}{2}X\frac{\partial f}{\partial \sigma}\sum_{n=0}^{\infty}\frac{\partial r}{\partial \zeta_n}\frac{\partial \zeta_n}{\partial X} - \frac{1}{2}X\frac{\partial r}{\partial \sigma}\sum_{n=0}^{\infty}\frac{\partial f}{\partial \zeta_n}\frac{\partial \zeta_n}{\partial X}\right) \quad (6)$$

where $\zeta_n = (X^{n+1}/U^{n+2})\,d^{n+1}U/dT^{n+1}$, $(n = 0, 1, 2, \ldots)$, and the Prandtl Number $Pr = \mu c_p/\lambda$. If the parameters $\zeta_0, \zeta_1, \zeta_2, \ldots$ are small, Eqs. (5) and (6) can be solved by expanding the functions $f(\sigma;\ \zeta_0, \zeta_1, \ldots)$ and $r(\sigma;\ \zeta_0, \zeta_1, \ldots)$ in power series of the parameters $\zeta_0, \zeta_1, \zeta_2, \ldots$, as Moore pointed out. It should be noticed, however, that it is necessary for higher approximations to examine the functional relationship between ζ_n's for each case of $U(t)$.

A few years ago the present writer[2] pointed out that, so far as $x(dM_1/dx)$ can be expressed as a polynomial of M_1, the parameters $M_2, M_3, \ldots, M_n = (x^n/U)(d^nU/dx^n), \ldots$ are also polynomials of M_1, respectively. Consequently, the steady laminar boundary-layer equations in incompressible fluids are reduced to a series of ordinary differential equations by expanding the nondimensional stream function in a power series of M_1 alone. Actually, all the existing solutions satisfy the condition mentioned above. Similar to that, the writer would like to suggest the possible forms of $U(t)$ for which Eqs. (5) and (6) may be solved by expanding f and r in power series of the sole parameter ζ_0.

Now, because of the definition of ζ_n we have

$$\left.\begin{aligned} (X/U)(\partial\zeta_0/\partial T) &= \zeta_1 - 2\zeta_0{}^2 \\ (X/U)(\partial\zeta_1/\partial T) &= \zeta_2 - 3\zeta_1\zeta_0 \\ &\cdots\cdots \\ (X/U)(\partial\zeta_n/\partial T) &= \zeta_{n+1} - (n+2)\zeta_n\zeta_0 \\ &\cdots\cdots \end{aligned}\right\} \quad (7)$$

Therefore, if $(X/U)(\partial\zeta_0/\partial T)$ can be expressed as a polynomial of the parameter ζ_0, then $\zeta_1, \zeta_2, \ldots$ all become polynomials of ζ_0. In other words, Eqs. (5) and (6) contain ζ_0 alone as the parameter, in spite of taking account of the parameters containing higher order time derivatives of $U(t)$. Then, Eqs. (5) and (6) are reduced to

$$\frac{\partial^3 f}{\partial \sigma^3} + f\frac{\partial^2 f}{\partial \sigma^2} = -8\zeta_0 + 2\left(2\zeta_0 + \frac{\partial^2 f}{\partial \sigma \partial \zeta_0}\zeta_0\right)\frac{\partial f}{\partial \sigma} - 2\frac{\partial^2 f}{\partial \sigma^2}\frac{\partial f}{\partial \zeta_0}\zeta_0 + 4\left(\frac{X}{U}\frac{\partial \zeta_0}{\partial T}\right)\frac{\partial^2 f}{\partial \sigma \partial \zeta_0} + 2\zeta_0\sigma\frac{\partial^2 f}{\partial \sigma^2} \quad (8)$$

$$\frac{\partial^2 r}{\partial \sigma^2} + Pr\, f\frac{\partial r}{\partial \sigma} + \frac{1}{2}Pr\left(\frac{\partial^2 f}{\partial \sigma^2}\right)^2 = 4\,Pr\left(2\zeta_0 r + \frac{1}{2}\zeta_0\sigma\frac{\partial r}{\partial \sigma} + \left(\frac{X}{U}\frac{\partial \zeta_0}{\partial T}\right)\frac{\partial r}{\partial \zeta_0} + \frac{1}{2}\frac{\partial f}{\partial \sigma}\frac{\partial r}{\partial \zeta_0}\zeta_0 - \frac{1}{2}\frac{\partial r}{\partial \sigma}\frac{\partial f}{\partial \zeta_0}\zeta_0\right) \quad (9)$$

Substituting

$$f(\sigma, \zeta_0) \equiv \sum_{n=0}^{\infty}\zeta_0{}^n F_n(\sigma) \quad (10)$$

$$r(\sigma, \zeta_0) \equiv \sum_{n=0}^{\infty}\zeta_0{}^n R_n(\sigma) \quad (11)$$

into Eqs. (8) and (9) and equating coefficients of the same power of ζ_0, we obtain a series of ordinary differential equations for the F_n and R_n's. Finally, they can be solved numerically, at least.

Some examples of $U(t)$ appropriate to the above condition are as follows:

(1) $U = U_0 T^m$:

$$\zeta_0 = \frac{mX}{UT}, \quad \zeta_1 = \frac{m-1}{m}\zeta_0, \ldots$$

$$\zeta_n = \frac{(m-1)(m-2)\ldots(m-n)}{m^n}\zeta_0{}^{n+1}, \ldots$$

$$\frac{X}{U}\frac{\partial \zeta_0}{\partial T} = -\frac{m+1}{m}\zeta_0{}^2$$

(2) $U = U_0 e^{AT}$:

$$\zeta_0 = XA/U$$

$$\zeta_1 = \zeta_0{}^2, \ldots, \zeta_n = \zeta_0{}^{n+1}, \ldots$$

$$(X/U)(\partial\zeta_0/\partial T) = -\zeta_0{}^2$$

(3) $U = U_0(1 + AT)$:

$$\zeta_0 = \frac{XU_0A}{U^2}, \quad \zeta_n = 0 \quad (n \geq 1)$$

$$(X/U)(\partial\zeta_0/\partial T) = -2\zeta_0{}^2$$

It is necessary to solve the series of the differential equations for F_n and R_n's, in order to discuss in detail. It is possible, however, to discuss the nature of time-dependence of velocity profile by inspecting the forms of the parameter ζ_0, which determines the velocity profile uniquely. For example, in the case of $U =$

$U_0 T^m$, a given velocity profile moves up- or downstream as time passes, or it stands still, according to the value of m—i.e.,

$m >$	0,	moves downstream
$m =$	0,	stands still (steady solution)
$0 > m >$	-1,	moves downstream
$m =$	-1,	stands still
$m <$	-1,	moves upstream

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Errata to "The Aerodynamic Forces on Low Aspect Ratio Wings Oscillating in an Incompressible Flow"[1]

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January, 1953

THE AERODYNAMIC COEFFICIENTS L_α and M_α for very low aspect ratio triangular wings presented in Section (VIII) of reference 1 are incorrect and should read as follows:

$$L_\alpha = \frac{\text{A.R.}}{2}\left[\frac{2}{3} - \frac{13i}{6k} - \frac{1}{k^2}\right]$$

$$M_\alpha = \frac{\text{A.R.}}{8}\left[\frac{46}{15} - \frac{9i}{k} - \frac{10}{3k^2}\right]$$

The definitions of the coefficients L_h, L_α, M_h, etc., are also incorrect and should read as follows:

$$L_h = \frac{2c}{S}\int_{-b}^{b} L_h' \, dy$$

$$L_\alpha = \frac{2c}{S}\int_{-b}^{b} L_\alpha' \, dy$$

$$M_h = \frac{2c}{S}\int_{-b}^{b} M_h' \, dy, \text{ etc.}$$

where the aerodynamic force coefficients L_h', L_α', M_h', etc., are defined in references 2 and 3.

The curve in Figure 4 corresponding to infinite aspect ratio is incomplete. It should continue across the real axis at 1.6 and return again to the real axis at 2.0.

References

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* The writers wish to thank H. Thompson and Dr. J. H. Chadwick for pointing out the corrections presented herein.

The Aerodynamic Profile as Acoustic Noise Generator

(*Concluded from page 282*)

profile noise is controlled by the air turbulence ahead of the profile, which means a fast-moving profile is an effective converter of weak ambient turbulence into powerful noise.

Conclusions

(1) The total noise of a propeller is composed of the rotational noise and the profile or vortex noise. The rotational noise has been theoretically studied. Measurements and theory are in good agreement. A current explanation of the process causing the profile noise assumes the vortices leaving the profile to generate the noise.

(2) A sound-room test with boundary-layer removal on a spinning blade proves that the vortices leaving the profile do not primarily cause the profile noise.

(3) Two more sound-room tests seem to indicate that the ambient air turbulence ahead of the profile is primarily causing the profile noise.

(4) A flight test indicates that under actual flight conditions the profile noise may be much more important than the model tests suggest. The fact that, based on the turbulence concept, the center frequency of the profile noise measured in flight can be calculated again supports the turbulence concept.

(5) If the new concept of the process causing the profile noise holds true, sound-room measurements of propeller noise cannot be applied to flight conditions. Also, full-size propellers must be much noisier when traveling in bumpy air than when traveling in almost turbulence-free air.

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